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Selected Bibliography of NACA-NASA Aircraft Icing Publications

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FOREWORD

In the 1940's and 50's NACA[1] was heavily engaged in research to develop suitable ice protection methods for the aircraft of that period. The work was conducted both at the Lewis Research Center, Cleveland, Ohio, and at the Ames Research Center, Moffett Field, California. NACA devoted several hundred man-years of research to the aircraft icing problem. During this same period, many others in the United States, as well as in Canada, Europe, Great Britain, and Russia were also working on the aircraft icing problem.

In the mid 1950's when the hot-air ice protection system was perfected for the large jet transports such as the KC 135, NACA terminated its large icing program. Lewis, however, continued to make available its 6- by 9-foot Icing Research Tunnel to the aircraft industry for developing and certifying ice protection equipment. These testing activities remained at a low level during the 1960's and early 70's. In the last few years, however, the number of requests for testing in the tunnel has steadily increased to the point where the tunnel is now continually occupied.

In the 1978 Aircraft Icing Workshop,[2] the recommendation was made that before attacking what appeared to be a new icing problem we should study the icing work of the 1940's and 50's. The documents of that period were so old, however, that they were not listed in the modern computerized library search systems, and some of these documents were out of print. Fortunately, U. H. von Glahn had prepared a selected bibliography of the NACA-NASA publications in aircraft icing. This bibliography was furnished to those who requested information about the NACA works. But some of the citations in the bibliography were those that were out of print.

In 1979, both the AGARD Working Group (WG-09) on Rotorcraft Icing and the Helicopter Icing Panel SAE AC-9 Committee urged NASA to reissue the publications cited in von Glahn's bibliography. Concurrently, industry and other government organizations requested that these reports be reissued.

The present report was prepared in response to those requests. The items contained in this report are as follows:

1. A reprint of a survey article by U. H. von Glahn entitled "The Icing Problem: Current Status of NACA Techniques and Research." The status report presents the main results of the NACA icing program from 1940 to 1950.

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[1]The National Advisory Committee for Aeronautics, now the National Aeronautics and Space Administration (NASA).

[2]Held at Lewis Research Center, Cleveland, Ohio, July 19-21, 1978. ("Aircraft Icing," NASA CP-2086, FAA-RD-78-109.)

2. A selected bibliography of 132 NACA-NASA aircraft icing publications as subsequently compiled by U. H. von Glahn. It includes publications from 1940 to 1962.

3. A technical summary of each document cited in the selected bibliography except for document 132.

4. A microfiche copy of each document cited in the selected bibliography except for document 132. A full-size hard copy or a microfiche copy of it may be obtained from the National Technical Information Service.

This report and each document cited in its selected bibliography have been incorporated into RECON, NASA's computerized technical information data bank and are retrievable. Full-size copies of these documents may be purchased from the National Technical Information Service, Springfield, Virginia, with the exception of two reports, 125 and 131. These two are available from the Society of Automotive Engineers.

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THE ICING PROBLEM - CURRENT STATUS OF NACA TECHNIQUES AND RESEARCH

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Icing of aircraft components such as airfoil surfaces and engine-inlet systems similar to those shown in figure 1 creates a serious operational problem. Aircraft are now capable of flying in icing clouds without difficulty, however, because research by the NACA and others has provided the engineering basis for icing protection systems. This paper summarizes some of the techniques used in NACA programs to solve aircraft icing problems and indicates the scope of the data available for the design of aircraft icing protection systems. In addition, appendixes A to C discuss the NACA Lewis icing facilities in detail, specific test equipment and techniques used in conducting tests in icing wind tunnels, and several icing instruments.

Icing of aircraft surfaces occurs when liquid cloud droplets cooled below the freezing temperature impinge on a surface that is also below freezing. All surfaces that are exposed to the direct impingement of supercooled water droplets therefore may require icing protection (fig. 2). The size and extent of icing on an airplane component is a function of cloud liquid-water content, droplet size, and air temperature, physical dimensions and shape of the component (size, shape, and attitude), and operating conditions (airspeed and altitude).

A body moving through a cloud of water droplets, in general, will not intercept all the droplets originally contained in the volume of air swept out by the projected frontal area of the body (fig. 3). As the droplets reach the vicinity of the body, the air streamlines flow around the body. The droplets, because of their momentum, tend to maintain straight paths toward the body; however, a drag force imposed by the relative velocity of the air with respect to a droplet tends to cause the droplet to follow the air streamlines. The relative magnitudes of the momentum and drag forces determine the droplet path. The path of droplets in the flow field can be determined analytically with particle trajectory equations. In order to do this, however, the size of the cloud droplets must be known. This information has been obtained with instrumented aircraft in flight through icing clouds. Two of the most widely used methods of obtaining cloud icing data are rotating multicylinders and the pressure-type icing-rate meter.

The rotating-multicylinder method has been used extensively to collect data on both droplet-size distribution and liquid-water content in supercooled clouds (refs. 1 to 4). The collection of ice by the cylinders is similar to the collection of ice by airplane components. Therefore, the

data obtained by this method have been valuable in designing icing protection systems for airplanes. In this method, several cylinders of different diameter rotating on a common axis are exposed from an aircraft in flight or in an icing tunnel to supercooled cloud droplets as shown in figure 4. During the exposure period, the cylinders collect ice. The cylinders are rotated in order to obtain uniform ice collection around the circumference and thereby to preserve a circular cross section.

After exposure, the diameters of the iced cylinders are measured and the iced cylinders are weighed. The measurement of droplet size and water content is based on the principle that cylinders of different sizes collect different quantities of ice per unit frontal area. The ice collection of each cylinder is expressed in terms of a collection efficiency that has been obtained theoretically. The liquid water content, average droplet size, and droplet-size distribution are obtained by a comparison of the measured weight of ice collected on each cylinder with calculated values of collection efficiency. The method is applicable only in clouds where the temperature is below 0° C.

The pressure-type instrument (ref. 5) operates on the differential pressure created when small total pressure holes plug with ice accretions, as illustrated in the sketch of figure 5. The small total-pressure holes in the ice-collecting element, which are vented to static pressure through a small orifice, are balanced against a non-vented, ice-free total pressure in a differential pressure switch. When these small total-pressure holes plug from ice accretion, the pressure in the corresponding side of the pressure switch approaches static by bleeding through the static orifice, and a differential pressure is created between the iced and ice-free systems. Continuous operation is obtained by allowing the differential pressure switch to energize an electrical heater that de-ices the ice-plugged total-pressure holes. The pressures in the two systems then tend to equalize, opening the pressure switch and allowing the cycle to be repeated. The heat-off time of this cyclic process is used as a measure of the period of time required to plug the holes. This period of time is a function of the rate at which ice accumulates on the element containing the holes, because the amount of ice accretion required for plugging is a constant value. The duration of the heat-off period is calibrated against a measured icing rate. An NACA flight-type film recorder is used to record continuously the duration of the heat-off or icing period, the heat-on or de-icing period, the indicated airspeed, the air temperature, and the altitude. The icing rate is then used to calculate the water content of the icing cloud. This instrument is limited by water run-off at air temperatures near 0° C and high water contents, as are the rotating multi-cylinders. Also, it does not measure droplet size. Other icing instruments are discussed in appendix C.

In general, the average droplet size in icing clouds is in the range of 10 to 25 microns in diameter. In stratus clouds the maximum water content is about 1.5 grams per cubic meter, while in cumulus clouds the water content

may be as high as 3.5 grams per cubic meter. Fortunately, these high water contents extend over only a short horizontal distance. For cumulus clouds the extent of such high water contents is only about 1/2 mile, while for stratus clouds the high water contents usually do not exceed 10 to 20 miles.

The data obtained by the rotating-multicylinder method have been of significance in establishing meteorological design criteria for aircraft icing protection systems. These data, however, were based on flights by only a few aircraft in deliberately sought icing conditions. The data from the pressure-type meter have been obtained on a routine flight basis by a cooperative program between the NACA, commercial airlines, and the United States Air Force. Some 50 aircraft were instrumented with these meters in various geographical areas of the world (fig. 6), including the North Atlantic, the continental United States, Alaska, the Pacific, and Japan. In addition, the program has been supplemented by in-flight weather reconnaissance reports from the Air Weather Service and Strategic Air Command aircraft over a two-year period. These data have been put on punch cards and are currently being analyzed on IBM equipment. Because most of the data obtained from routine flights apply to low altitudes, special efforts are being made to obtain data on the occurrence of icing at altitudes above 20,000 feet. Data obtained to date show that icing is rarely encountered about 30,000 feet because of the infrequency of clouds containing liquid water at the low temperatures associated with these altitudes. In addition, the severity of icing encountered above 30,000 feet is usually low except in scattered thunderstorm clouds.

The impingement characteristics and the initial rate of ice formation on aircraft components can be obtained by either theoretical trajectory studies or experimental means, once the water content and droplet sizes of icing clouds are available. Most of the NACA analytical studies of droplet trajectories about various bodies (refs. 6 to 13) utilize a differential analyzer (fig. 7), since experience has shown that even the simplest manual calculations are time-consuming and inaccurate. The use of the differential analyzer in this work is described in reference 14.

Typical results obtained from such a trajectory study are shown in figure 8, in which the local impingement rate on an airfoil is plotted as a function of surface distance from the leading edge. The data shown are for a 15 percent symmetrical airfoil of 8-foot chord, angle of attack of zero, airspeed of 150 knots, and average droplet sizes of 8 and 15 microns. The greatest impingement occurs at the stagnation region and decreases rapidly with surface distance from the leading edge. An increase in average droplet size from 8 to 15 microns increases the local impingement rates and causes the impingement area to extend farther aft than with the smaller droplets.

The differential analyzer is difficult to use for droplet trajectories about bodies with complex air flows. Therefore, a wind-tunnel method using

a dye-tracer technique (ref. 15) is often used to obtain experimentally the droplet impingement on these bodies. In this technique (fig. 9), water treated with known small quantities of water-soluble dye is sprayed into the airstream a large distance ahead of the body by nozzles. The surface of the body is covered with blotter paper upon which the dyed water droplets impinge and are absorbed. At the point of droplet impact, a permanent dye trace is obtained. The amount of dye obtained in a measured time interval can be determined by a colorimetric analysis of punched-out segments of blotted paper (fig. 9) and converted into the quantity of water that produced the dye trace. The maximum extent of impingement of the local dye or water deposit over the entire wetted surface will yield the total amount of water collected by the body. This experimental technique requires a knowledge of the droplet-size distribution and water content of the spray cloud. Methods of obtaining these parameters have been worked out and are included in the report concerning the technique (ref. 15).

The total water catch and the extent of impingement on an airfoil surface obtained by the differential analyzer are compared in figure 10 with the experimental data (unpublished). These data are shown as a function of an impingement parameter which, in this case, depends primarily on the droplet size squared, wing chord, and airspeed (ref. 16). These are typical results for a 15 percent-thick symmetrical wing at zero angle of attack.

From a knowledge of the droplet impingement characteristics and meteorological parameters, the local water impingement rate or icing rate on component surfaces can be calculated. Unfortunately, the shape of the resultant ice formation, which has a large effect on the aerodynamic penalties associated with component icing, can only be estimated based on limited experimental data, since the ice-formation shape is also a function of airfoil sweep angle, air temperature, and aircraft speed. Ice shapes can be generalized into two primary shapes, rime icing and heavy glaze icing (fig. 11). Rime icing is associated primarily with low air temperatures and results in relatively streamlined ice formations that blend into the body shape and cause little aerodynamic penalty. Heavy glaze icing results from high water contents, large droplets, and surface temperatures near freezing. This combination of meteorological conditions causes rough ice formations that protrude from the body surfaces into the airstream and cause large aerodynamic penalties.

Early attempts to measure these penalties were made in flight through icing clouds. However, the general advantages of doing icing research in a tunnel where conditions can be controlled were recognized, and an icing research tunnel was built at the NACA Lewis laboratory. The Lewis icing tunnel is a single-return closed-throat tunnel, the general arrangement of which is shown in figure 12. The test section is rectangular in shape, 9 feet wide, 6 feet high, and 20 feet long. The maximum tunnel airspeed with

icing conditions and with a large model in the test section is about 260 knots. Air temperatures as low as -40° C can be obtained, although most tests are conducted in the range of -3° to -20° C.

Icing conditions similar to those encountered in the atmosphere are created by a battery of air-water atomizing nozzles. A view of the spray system looking downstream into the test section is shown in figure 13. The spray nozzles are mounted in six horizontal spray bars and located to give a uniform cloud approximately 4- by 4-feet in the test section. This cloud conforms to natural icing clouds measured in flight. Details of this icing tunnel, its equipment and instrumentation, as well as of several high-speed icing duct tunnels, are given in appendixes A and B.

In order to determine the magnitude of the aerodynamic penalties associated with icing of lifting surfaces, airfoils of different sizes, thicknesses, and shapes were tested in the Lewis icing tunnel over a wide range of angles of attack and icing conditions (refs. 17 and 18). Section-drag measurements during icing were obtained by means of an integrating wake survey rake (fig. 14) and the tunnel force-measuring balance system. Lift and pitching moments were also measured with the balance system.

A typical lift and drag curve for an NACA 0011 airfoil at an angle of attack of 2.3° is shown in figure 15 as a function of time in glaze icing, together with a picture of the ice formation at the end of 18 minutes of icing (unpublished data). It is apparent that under these operating conditions the loss in lift of 12 percent and the increase in section drag of 270 percent after 18 minutes of icing could constitute a serious problem for an aircraft.

Ice formations on aircraft components can be prevented by flowing or spraying temperature-depressant fluids over the component surfaces (ref. 19) or by heating the surfaces (refs. 18 to 23). The work of the NACA has emphasized the use of heat for icing protection. Component icing can be prevented by thermal means in two ways: (1) The surfaces can be raised to a temperature just sufficient to maintain the impinging water in a liquid state over the entire surface, or (2) the surfaces can be supplied sufficient heat to evaporate the impinging water in a specified distance aft of the impingement area while the remainder of the surface is unheated. Obviously, it takes more heat per unit surface area to evaporate the water than to maintain the same surface just above 0° C. Calculations show, however (ref. 23), that the total area that requires heating must also be considered in evaluating the total heat requirement. Therefore, the size of the component will generally influence which of the two methods of ice prevention is used.

The heat supplied to a component for icing protection (fig. 16) warms the impinging water to the component surface temperature and evaporates part or all of the impinging water. Some heat is lost to the ambient air by con-

vection. The relative magnitudes of the external heat losses shown in figure 16 are typical for anti-icing a wing surface and are shown as a function of surface distance aft of an airfoil leading edge. In addition, some of the heat is lost to adjacent structure by conduction. The external heat-transfer processes from a heated, wetted surface were postulated by J. K. Hardy (refs. 24 and 25). The processes were substantiated by in-flight data obtained by the staff of the NACA Ames laboratory (ref. 20). The Ames tests employed an aircraft with electrically heated dorsal wings (fig. 17). The electrically heated airfoils were instrumented with thermocouples (fig. 18) so that, with the conductivity and thickness of the material known, the internal heat loss could be calculated. Because of the thin outer skin, the chordwise heat conduction was considered negligible. Hence, the external local heat transfer was obtained from the total power input and the internal heat loss.

Typical results obtained from these studies are shown in figure 16. These data show that the heat for evaporating the impinging water and that lost to the ambient air by convection are approximately equal. The heat required to raise the impinging water to the surface temperature is only a small fraction of the total heat input. At the leading edge the heat flow is about 3900 Btu/(hr)(sq ft), while aft of the impingement area the local heat flow is 2400 Btu/(hr)(sq ft) or less.

In order to demonstrate that the results obtained in icing conditions in the tunnel were the same as those obtained in flight, a wing section carried on the C-46 aircraft during the Ames laboratory flight tests was also tested in the icing tunnel, and the data were compared (ref. 21). The results showed that in similar icing conditions, as determined by measurements of the cloud conditions by similar instruments, the data agreed satisfactorily.

For high-speed, high-altitude aircraft, the icing-protection heat requirements (due to changes in heat transfer and evaporation considerations influenced by speed and altitude) of a thermal anti-icing system are excessive. For example, calculations showed that the heat required for evaporating all the water impinging on a jet powered transport exceeds 7,000,000 Btu/hr. Since this heat would be taken from the jet engines, a severe performance penalty would result (ref. 23).

In order to reduce the thermal requirements for airframe components, cyclic de-icing systems were studied. In cyclic de-icing, ice is permitted to form on the airplane surfaces and is then removed periodically by a short intense application of heat. During the heating period, the bond between the surface and the ice is melted and the ice is removed by aerodynamic forces. Only a few components or sections of a component are heated at a time, the rest being allowed to ice. Because the components are heated successively, proper grouping of the components permits shifting of heat from one group to another and thereby maintaining a constant heat load. The icing or heat off time is determined by the amount of ice that can be tolerated on a component without seriously affecting its performance.

Numerous thermal cyclic de-icing systems were studied in the Lewis icing tunnel, typical of which was the hot gas cyclically de-iced airfoil shown schematically in figure 19. The initial NACA design consisted of a conventional double skin, a two-way hot gas supply duct with valves for cycling the hot gas into the plenum or D-duct running spanwise at the leading edge, and a conducting fin attached to the supply duct and airfoil skin at the leading edge near the stagnation region (ref. 26). A two-way gas-supply duct was used so that the hot gas would flow outboard and return in an adjoining rear passage in order to maintain a constantly hot supply line. The valves in the supply line open in spanwise sequence, thereby permitting a constant flow of gas in the forward passage and greatly avoiding thermal lags. Because the forward passage is continuously heated, the fin conducts heat to the skin at the stagnation region, thereby providing a narrow ice-free spanwise parting strip. This ice-free parting strip splits the ice cap that usually forms over the nose of the airfoil and facilitates ice removal by aerodynamic forces during the heating period.

The model was extensively instrumented with thermocouples in the skin and structural members and in the air passages in chordwise planes at several spanwise locations. Flow to the various sections was carefully metered by orifices in the air-supply lines. Timing of the fast-acting pappet-type cycle valves was made with electronic timers.

The results obtained from extensive studies of this model (refs. 26 and 27) show that savings in total heat input of as much as 75 to 90 percent of the heat required to prevent ice on the same wing were achieved. Similar results were obtained at both the NACA (ref. 28) and NAE facilities with electrically de-iced airfoils. Subsequent studies with a 36° swept wing (ref. 17) show that the tangential air-flow component along the span is sufficient to eliminate the need of a spanwise ice-free parting strip for facilitating removal of the ice formation. Systems similar to the NACA hot-air cyclic de-icing systems are currently being used by some manufacturers in the latest jet aircraft.

The use of a cyclic de-icing system necessitates an evaluation of the aerodynamic penalties associated with the ice formations permitted to build up during the unheated portion of a cycle (fig. 20). A number of airfoil models were tested to obtain the drag characteristics of cyclically de-iced airfoils in icing conditions (refs. 17 and 18). The results of these tests show that the drag and lift changes averaged over a cycle do not constitute a serious operational hazard if the length of the cycle can be adjusted to the serverity of the icing condition.

In addition to thermal de-icing systems, ice can be removed from most airfoil surfaces by a mechanical de-icing system consisting of a high-pressure pneumatic boot (fig. 21). In this system, inflatable tubes are sandwiched between two layers of rubber or neoprene. When ice forms on the outer surface of the boot, compressed air is bled periodically into the tubes which then inflate for a period of 3 to 6 seconds. Vacuum is applied

to the tubes to maintain the surface flush during the off part of the cycle. Studies in the icing tunnel show that these de-icers will effectively remove the main ice formations; however, the small flakes of residual ice adhering after the removal cycle will cause a section-drag increase of up to about 30 percent (unpublished data). Experimental studies indicate that removal of these residual ice formations by sublimation is a long process (ref. 29). These drag increases, therefore, can penalize aircraft performance over a much longer portion of the entire flight than for just the duration of the icing encounter.

The engine is the most vital component on the airplane requiring icing protection. Work on icing protection for engine air inlets and induction systems covered piston and jet engines. The work on piston engines, summarized in an NACA technical report (ref. 30), led to the recommendations incorporated in figure 22 for a typical arrangement of an engine induction system. Such a design includes (1) an air inlet, which reduces the intake of water and snow to a minimum by utilizing the inertia and momentum differences between air and water particles to separate the droplets out of the air at the inlet, (2) aerodynamically clean flow passages to prevent ice accretion on exposed parts, (3) air-metering devices located in a warm, dry region, (4) throttle and throttle bodies kept above freezing, and (5) fuel injected downstream of the heated surfaces to prevent fuel-evaporation icing. Aircraft that incorporate many of these features, including the inlet type shown, are the Convair-240 and some versions of the Lockheed Constellation.

The high speeds of jet-powered aircraft and the large engine air flows necessitated a reappraisal of the icing problem for jet engines compared with that for the reciprocating engine. While the early centrifugal jet engines were not generally critical with respect to inlet and engine icing, because of engine geometry and structure, the axial-flow engines were adversely affected by icing. The icing of engine inlet guide vanes (refs. 31 to 33) and inlet screens constituted an icing hazard (fig. 23) that not only reduced the available thrust and increased specific fuel consumption but could cause engine failure. The icing hazard of a fixed inlet screen was aptly demonstrated by the simultaneous loss of eight F-84 aircraft over Indiana after a brief encounter with severe icing conditions in 1951. Tests in the Lewis icing tunnel also showed that the pressure loss associated with icing of guide vanes could cause large pressure losses and hence thrust losses (ref. 33). Several icing protection systems using alcohol or hot gas injection into the airstream to provide protection for the screen, accessory housing, and guide vanes were studied by NACA and NAE. With these systems, however, contamination of the compressor air (which is often used for cabin pressurization) or large thrust losses resulted.

The use of thermal icing protection for most engine components appeared most feasible. In the case of the screen, however, electro-thermal means did not appear attractive because of the large heating rates required. Consequently, the complete elimination of the screen or retraction during an

icing encounter appeared mandatory. Elimination of the screen exposed the engine to damage from ice chunks breaking off from unprotected components ahead of the compressor and entering the engine. Practically all types of axial-flow engines tested at the military services Mt. Washington icing facility have suffered partial or complete engine failure from ingestion of such ice chunks. Thermal icing protection is required, therefore, for all components of the engine inlet that may shed these ice chunks if left unprotected.

In the axial-flow engine the inlet guide vanes upstream of the compressor ice quickly. Complete icing protection of these members is required if the engine is to function in icing conditions. A study of means for heating the guide vanes internally with hot air was conducted with a cascade of five vanes mounted in a rectangular duct set in the icing tunnel (fig. 24). Ice collected on the leading and trailing edges of the highly cambered blades used for inlet guide vanes. For this reason, a saving of 50 percent of the heating air flow (fig. 25) is achieved if the interior of the vane is partitioned to restrict this hot air to the areas of the blade on which ice collects. This partitioning of guide vanes has been adopted for some current engines.

Because the engine accessory dome collects ice that may break off after reaching a destructive size and enter the engine, research was conducted on the heating requirements for several jet-engine accessory domes. An electrical icing protection system was used in order to obtain selective and controlled heating and thereby verify theoretical local heat-transfer data (ref. 22 and unpublished data). The domes were tested also with rotation to simulate turboprop installations in order to study the effect of rotation on heating requirements. In general, the rotational effect was negligible for the size models tested.

While it is apparent that aircraft operating at relatively low airspeeds and at altitudes less than 20,000 feet will require airframe icing protection equipment, high-speed, high-altitude aircraft, on the other hand, may require little if any such equipment. These aircraft cruise at altitudes where little or no icing occurs. Studies in high-speed icing duct tunnels (refs. 34 to 36) show that icing can occur at speeds up to a Mach number of approximately 1.3; however, because of aerodynamic heating of the surfaces at this high speed, such icing conditions would require low air temperatures. The frequency of encountering severe icing at low air temperatures on a statistical probability basis is almost negligible. The icing problem for these aircraft, therefore, is confined primarily to climb and let down conditions. Because of their high rates of ascent and descent, the icing encounters for these aircraft are of short duration. Consequently, the flight plan and aircraft mission are becoming increasingly more important in determining the necessity for airframe icing protection equipment.

A limited operational analysis of an interceptor and a transport aircraft was presented in a paper by the author at an NACA conference on Some Problems of Aircraft Operation (Nov. 17-18, 1954). This study showed that thin-winged interceptor aircraft with a high rate of climb and descent and cruising at high altitude do not appear to require an airframe icing protection system except possibly during a landing operation. This study suggested that a partial or a simple one-shot icing protection system could be installed at minimum weight, structural, and performance penalty to cope with an icing encounter during landing. The study also concluded that jet transports, because of their slower rates of ascent and descent, should be provided with an airframe icing protection system. Since the engine is so vulnerable to ice damage, complete engine protection is required for both types of aircraft.

In summary, therefore, the NACA research programs have provided sufficient data or have established techniques whereby icing-protection requirements for most aircraft components can be determined sufficiently accurately for engineering purposes. The data obtained have been generalized whenever possible; however, it is recognized that certain specific installations at present still require testing in an icing tunnel or in flight. Meteorological studies are providing sufficient information on conditions conducive to icing on which to base the design requirements of aircraft components and to determine the need of icing protection for specific aircraft and flight plans. While this paper deals primarily with NACA studies in icing research, the contributions of other agencies including the groups operating at the Mt. Washington facilities, the U.S. military establishments, the U. S. aviation industry, the Canadian NAE, and other groups in the United States, Great Britain, and France must also be recognized. All these groups have cooperated and exchanged ideas that have aided in the successful solution of many icing problems.

APPENDIX A

ICING TUNNEL FACILITIES

The amount of time required for both aircraft and equipment maintenance to obtain sufficient data in flight toward the solution of icing problems, together with the difficulty of obtaining data in specified, controlled icing conditions, resulted in the design and construction of an icing wind tunnel at the NACA Lewis laboratory in 1943-1944.

The Lewis icing tunnel is a single-return closed-throat tunnel, the general arrangement of which is shown in figures 12 and 26. The tunnel is constructed of steel plate and is insulated with a 3-inch thickness of Fiberglas. The outer nonstructural shell covering the insulation is made of 1/8-inch steel sheets.

The tunnel is anchored at each end of the test section and at each end of the drive motor and supported by columns and sliding expansion joints at all other points in order to allow movement due to temperature stresses. The over-all size of the tunnel shell is about 198 feet long and about 75 feet wide. The test section and a portion of the entrance cone and diffuser are surrounded by a steel housing to provide space for the essential test equipment and operating personnel. This space is called the test chamber. Because the test section is vented to the chamber, the air pressure decreases in the chamber during operation of the tunnel (normally less than 3 in. Hg). An air lock is provided to permit access by personnel to the chamber during a run.

The test chamber contains three floor levels: the ground floor, containing electrical, thermocouple, water, and balance-scale equipment; the second floor, containing the test section of the tunnel and the various controls, manometers, recording instruments, and associated equipment; and the third floor, containing auxiliary measuring equipment. Personnel access to the tunnel is generally from the second floor of the test chamber, while models are lowered into the test section from the third floor through a removable 48- by 140-inch access hatch in the roof of the test section.

The test section is rectangular in shape, 9 feet wide, 6 feet high, and 20 feet long. The air enters the test section from a large rectangular section giving a contraction ratio of about 14 to 1. The test section of the tunnel is provided with a turntable on which models can be mounted, as well as side-wall trunnion mounts. The maximum tunnel airspeed with icing conditions and a large model in the test section is 260 knots.

Windows are provided on both sides and in the roof of the tunnel test section to allow observation of models during a test. The windows in the tunnel sides are laminated, electrically heated units similar to windshields

on many aircraft, while the windows in the test section roof are unheated. The power supplied to the new windows currently being installed is 500 watts per square foot. The temperature of the plastic inner layer of the window is detected by a nickel wire element. This element is used in a bridge circuit to control the window temperature.

Turning vanes are used in all right-angle corners of the tunnel. The vanes downstream of the test section and ahead of the drive fan are steam-heated to prevent icing.

The drive motor for the tunnel develops 4160 horsepower. The drive consists of a doubly fed wound-rotor induction motor. Power is supplied directly to the stator, while the power for the rotor is supplied by a four-machine variable and fixed frequency setup. A variable-speed d-c motor, driven according to the Ward-Leonard system, drives an a-c generator. The generator supplies the power to the tunnel drive-motor rotor. The speed of the drive motor is governed by the speed of the a-c generator or d-c motor, the speed of these machines being controlled by varying the voltage to the d-c motor. The drive motor has a speed range from 0 to 540 rpm. A 200,000-cubic-foot-per-minute, 50-horsepower blower is used to cool the drive motor.

The tunnel drive motor is coupled directly to a 25-foot-diameter drive fan with 12 blades. The fan blades are wooden, with the leading edges of the blades protected by neoprene abrasion shoes. Stationary contra-vanes are used ahead of the fan.

A ventilating tower is located downstream of the drive motor. This tower permits an exchange of tunnel air with outside air. The primary use of this unit has been to provide an additional cooling load to help regulate the tunnel air temperature for certain test conditions. In addition, a finned-tube heat exchanger with a capacity of 5,000,000 Btu per hour is available to aid in regulating the tunnel air temperature.

A compression-type refrigeration system located in a nearby building is used to cool the tunnel air to the required icing condition. The tunnel is cooled by passing the air over a bank of refrigerated finned heat exchangers located in an area between the drive motor and the tunnel spray system. The total refrigeration capacity is about 7700 tons. The normal cooling load for the icing tunnel requires from 1200 to 2100 tons; however, this requirement varies with climatic conditions. Air temperatures as low as -40° C can be obtained, although most tests are conducted in the range of -3° to -20° C.

Icing conditions similar to those encountered in the atmosphere are created by a battery of air-water atomizing nozzles. A view of the spray system looking downstream into the test section is shown in figure 13. The spray nozzles are mounted in six horizontal spray bars and located to give a uniform cloud approximately 4- by 4-feet in the test section. Controls for the spray system are located in airfoil-shaped enclosures at one end of each strut.

A sketch of the air-water atomizing nozzles used in the spray system is shown in figure 27. The nozzle assembly consists of air and water supply lines, steam line to prevent icing of the entire strut, and the spray nozzle (Inconel). Approximately 80 nozzles are used to obtain an adequate cloud in the tunnel. The nozzles were specially developed for the tunnel to yield droplet sizes ranging from a mean effective size of 4 microns at low water flows to about 20 microns at maximum water flows. Air pressures of 60 to 80 pounds per square inch are used normally to atomize the water, while the water pressures range from a few pounds above the air-pressure values up to 140 pounds per square inch. The large water-pressure values correspond to large water flows and large droplet sizes. The droplets produced by these nozzles are not uniform in size but vary approximately in accordance with a Langmuir D or E drop-size distribution (ref. 37). For a constant water flow, the liquid-water content in the tunnel varies with the airspeed. In addition, the contraction of the tunnel entrance cone affects the droplet paths and local water concentration in the tunnel. Consequently, maximum or minimum values of water content and droplet size independent of tunnel airspeed cannot be stated explicitly.

The water used for the spray system passes through a 500-gallon-per-hour-capacity demineralizer. The demineralizer consists of two anion and cation filter beds that remove all minerals from the water, thereby preventing fouling and plugging of the spray system. From the demineralizer, the water is piped into a storage tank with a capacity of 750 gallons. The storage tank is kept full by a float switch that turns the demineralizer on and off to maintain a given water level in the storage tank. From the storage tank the water is piped to two turbine water pumps with a capacity of 5 gallons per minute each at 150 pounds per square inch gage. The water is pumped through three rotameters for flow mesasurement and then into a steam heat exchanger that heats the water to a temperature of 80° to 90° C. Heating of the water is necessary to prevent freeze-out of the water when it is air-atomized to cloud droplets in the tunnel. Following the heat exchanger the water is filtered at each strut control box. The water pressure is regulated at each strut by a pressure regulator controlled by the tunnel operator. The water pressure is sensed by a pressure transmitter, which changes water pressure to pneumatic pressure. The water pressures in each spray strut (in the form of pneumatic pressure) are indicated on a manometer board in the test chamber.

Air is furnished to the water-spray system from a service air line with a capacity of 6 pounds per second at 120 pounds per square inch. This air is passed through a pressure regulator, a steam heat exchanger (which heats the air to approximately 80° to 90° C), and a two-stage filter before entering the strut control boxes. The air pressure is also controlled from the test-chamber control area.

A separate spray system consisting of 4 to 9 nozzles is used to inject dyed water into the tunnel for experimental studies of droplet impingement characteristics of various bodies (ref. 15).

A balance frame is provided with a 6-component force-measuring scale system. Data are recorded automatically on tapes at each balance. Electrically heated co-axial pressure tubes are used to obtain pressure data. All pressure data are recorded photographically from multi-tube manometer boards. Temperature data obtained with copper-constantan thermocouples are recorded on automatic flight recorders. The control equipment includes variable transformers for power control to models, automatic temperature controller for heated air to models, and various recording instruments for heat-source control. Standard instruments are used to record tunnel airspeed and air temperature. An NACA pressure-type icing-rate meter is used to measure the liquid-water content of the tunnel atmosphere. Special instrumentation is added whenever required for a particular study.

Heated air for providing models with icing protection is supplied by three heat exchangers. The air from these exchangers is heated by the exhaust from a jet-engine combustion can. Each heat exchanger has a flow capacity of 1000 pounds per hour with pressure regulation up to 120 pounds per square inch. Orifices in each line allow a measurement of the flow from each exchanger. Constant air temperature over a wide range of air flows is obtained by an automatic flow control that regulates the amount of cold air permitted to mix with heated air from the exchangers.

Electric heating supplied to models for icing protection can be obtained from either a-c or d-c sources; however, a-c is generally preferred. The d-c system capacity is 28 volts and rated at 100 amperes. In addition, a 12-volt d-c system rated at 50 amperes is also available. A 29-volt a-c system rated at 50 amperes is available and is used for heater studies for which the heater load is normally run on d-c. A 110-volt single-phase system and a 208-volt, three-phase, 50-ampere system are available for large electrical loads. Selective power inputs (a-c three-phase system) to electrically heated models are metered (power recorded on a recording wattmeter) by means of 18 variable transformers rated at 3 amperes, 16 variable transformers rated at 9 amperes, and 3 variable transformers rated at 45 amperes. A 400-cycle inverter capable of supplying 1500 volt-amperes at 115 volts is also used for some instrument tests.

Electronic timers are available by which specified heating and icing periods for either electric or air heating systems can be controlled.

The 136-inch-high multi-tube manometer board is so arranged that it may operate as an integrating type or a standard board. A total of 298 readings can be obtained from the board. Additional U-tube and standard manometer boards are available as required. Most of the tubes are also connected to an air-purge system by which air is bled through the tubes back to the

model. An air-operated cylinder or pincher closes off the tubes at the manometer to prevent the purge air from blowing the manometer fluid out of the bonds. The purge air prevents the entry of water from the spray cloud into the tubes and blocking or freezing of the unheated portions of the pressure lines. During this purging procedure, no manometer-board readings are taken.

For aerodynamic studies of airfoils in icing conditions, the airfoil surfaces aft of the region protected by the icing protection system (called afterbody) are generally heated. This heating is required, since the turbulence level and supersaturated air in the test section cause a frost deposit on the cold portions of a model. These deposits have rarely been observed in natural flight icing. Such frost deposits increase the measured model drag. A steam line operating at +5 to -3 inches of mercury is used to heat these afterbodies. To avoid steam leakage from the model into the tunnel, the afterbody is operated at a negative pressure by means of a small ejector and a barometric condensor located externally of the model.

Photographs of ice formations during a test are obtained with high-speed electronic flash equipment, while conventional camera equipment is used for pictures taken in the tunnel at the conclusion of a test. Color photography has proved to be the most satisfactory for movie film recording of data in the presence of the spray cloud.

Airfoil models normally span the vertical height of the tunnel. Chords of these models have ranged from 13 to 96 inches or larger. Horizontal model mounting has also been used occasionally; however, because of wind-tunnel-wall interference effects, the vertical mounting is preferred. Bodies of revolution and inlets tested are normally less than 36 inches in diameter.

In addition to the 6- by 9-foot icing tunnel, two smaller high-speed icing-duct tunnel facilities are also used. Techniques equivalent to those just described are used in these tunnels. A schematic diagram of the 3.84- by 10-inch tunnel presented in figure 28 shows the inlet diffuser section with screens, the plenum chamber with flow-straightening tubes, the bell-mouth tunnel entry, the test section, and the outlet diffuser section. The tunnel is designed to provide a range of subsonic Mach numbers from 0.3 to 0.8 and a supersonic Mach number of 2.0. Altitudes up to 30,000 feet may be simulated.

A supply of refrigerated air initially at approximately -20° F and with a specific humidity of 5.0×10^{-4} pound of water per pound of dry air is conditioned to provide the desired temperatures and humidities at the tunnel test section. The humidity of the airstream is controlled by means of steam injected at a point sufficiently far upstream to ensure thorough mixing at the tunnel entry.

One wall of the tunnel contains a large glass section for observation and visual measurements. The other wall has five portholes for access to the inside of the tunnel and removable plugs for installation of instrumentation at various stations along the tunnel. Permanent instrumentation of the tunnel at the test section includes static-pressure taps along the top and bottom surfaces of the tunnel and pressure taps and thermocouples in the plenum chamber.

A schematic diagram of the component parts of a 12- by 12-inch icing duct tunnel is shown in figure 29. The tunnel characteristics are in general similar to the 3.84 - by 10-inch tunnel. Subsonic speeds up to a Mach number of 0.75 can be achieved with small airfoil models. For icing studies the airspeed is maintained in the subsonic and low supersonic speed ranges.

APPENDIX B

OPERATIONAL TECHNIQUES

The following are techniques used for model testing in the Lewis icing tunnel and associated facilities.

Thermocouple Installations

Whenever possible, all skin or surface thermocouples (copper-constantan) are peened into small holes drilled into the surface as shown in figure 30. The ball at the junction of the thermocouple is just large enough to fit into the hole, so that peening the surface around the ball will result in a firmly anchored thermocouple. The ball should be as close to the outer surface of the skin as possible. For very thin metal skins (0.005-inch stainless steel, e.g.) spot-welding the thermocouple on the inner surface of the skin is acceptable. The thermocouple leads should not be secured on the outer surface of the model, since ice will anchor on the leads. If splicing of thermocouple leads is required, such splices should be made in a protected, constant-temperature location, outside the model in the test chamber. All thermocouple leads should be protected against moisture; asbestos-covered wires are not generally recommended for models in icing conditions. Shielded thermocouples are recommended for obtaining measurements of hot air temperature, although a trailing thermocouple such as that shown in figure 30(b) is acceptable.

Tunnel Air Temperature

The tunnel air temperature is obtained with a probe that separates the entrained water from the airstream as shown in figure 31. The probe consists of a nose and rear cap and a housing containing a temperature-sensing element. Holes are located in the housing so that the air flows through the probe from the rear to the front of the probe. The locations of these holes are based on pressure-distribution studies. The water droplets, because of their inertia, do not enter the housing at the rear locations. Because the nose-cap diameter is larger than the housing diameter, the housing is protected from icing. The nose cap is allowed to ice. Thermal icing protection could be incorporated in the nose cap; however, an error in the indicated temperature would be incurred. The average temperature-recovery factor for these probes is about 84 percent and is constant over a range of Mach numbers from 0.2 to 1.0. In the NACA icing tunnel the probes are used to measure air temperature in the low-speed section upstream of the spray system and ahead of the contraction cone. The air temperature measured by these probes is therefore essentially a total air temperature. Because the tunnel is always at least saturated when the spray system is used, the ambi-

ent-air temperature in the test section is computed by conventional wet-air equations (ref. 21). The total air temperature measured in the low-speed section of the tunnel is used for a base in these calculations.

Temperatures from Rotating Bodies

A typical means used to transmit the temperatures from a rotating body to a recorder is shown schematically in figure 32. The thermocouple leads from the body are fed through a hollow motor shaft to the rear of a motor housing and through a thermocouple selector switch into a steam-filled jacket that rotates with the shaft. From the rotating jacket, copper leads are attached to a slip-ring and brush assembly. From this assembly, copper leads are again led into a steam-filled stationary jacket. Copper-constantan leads are used from the stationary jacket to a thermocouple selector unit and to a flight recorder. The steam jacket is used to provide a constant temperature at critical junctions in the thermocouple circuit, where the wire metal in the thermocouple leads is changed from copper and constantan to all copper and back again.

Pressure Tubes

In icing conditions all pressure tubes subject to water impingement (pitot-static tubes, tubes in survey rakes and in the boundary layer, etc.) must be protected against icing. In the Lewis icing tunnel such pressure tubes are generally electrically heated. A co-axial tube is used consisting of two concentric tubes separated by a woven glass sleeving insulation (fig. 33). The ends of the tubes exposed to the airstream are silver-soldered and shaped to obtain either static or total-pressure tubes. Tube sizes of 0.093- to 0.437-inch outside diameter and 0.057- to 0.393-inch inside diameter with wall thicknesses of 0.005 inch are in common usage. These tubes are made of Inconel. A special tube bender was developed by NACA personnel to avoid collapsing of the co-axial tubing during bending of the tubes to a desired shape.

Surface Pressure from Rotating Body

A scheme similar to that used to obtain temperatures from rotating bodies is also used to obtain surface pressure measurements. Pressure lines from a model are fed into a hollow shaft (fig. 34). Each tube is then allowed to vent into a chamber composed of the hollow shaft, bearings, and a stationary housing. All pressure sealing is accomplished by the bearings and felt seals. The pressure from each sealed chamber is then transmitted to a manometer. A water-jacket cooling system (not shown) is provided for high-rotational-speed operation. This pressure system permits simultaneous readings of many pressures and is generally limited only by the number of bearings used.

APPENDIX C

ICING INSTRUMENTS

The determination of liquid-water content and droplet-size distribution of natural and artificial clouds has received considerable attention in connection with cloud physics studies and, in particular, in aircraft icing studies. A knowledge of the liquid-water content and droplet-size distribution in clouds is of fundamental importance in evaluating rate and area of ice formation on various aircraft components, rate and area of erosion by impinging droplets on various aircraft surfaces such as radomes, reduction of visibility, attenuation of radar, and the basic mechanism of cloud formation and precipitation.

Numerous methods for determining these parameters have been proposed and tested, but each method suffers limitations as to accuracy or ease in obtaining or reducing the data to useful form. In some cases the limitations become very severe when measurements are attempted in high-speed airstreams. In addition to the rotating multicylinders and pressure-type icing-rate meter discussed in the test, some methods and techniques that have been widely employed to determine liquid-water content and/or droplet size are:

(1) Cloud camera
(2) Oil slides
(3) Oil-stream aeroscope
(4) Heated probes

The methods are described and discussed in references 38 to 40.

The use of cameras (fig. 35) to photograph droplets directly in a cloud (ref. 38) is based on fundamental principles and is basically a sound technique, but there are practical difficulties. Because of the high magnification required, the volume of the field of view is extremely small. As a result, the average number of droplets per 8- by 10-inch picture is small in clouds of moderate liquid-water contents. Therefore, a large number of pictures are required in order to obtain a size distribution. Since the magnification required is high, it is difficult to design a camera so that the object plane is outside the undisturbed airstream about an airplane or camera mount.

The oiled-slide technique, where a glass slide covered with a suitable oil is exposed to a droplet-laden airstream and is then photographed through a microscope, has been used also to determine droplet-size distributions. This method yields photographs with a large number of droplets per picture from which the droplet sizes may be measured. However, because of the relatively large size of the slide compared with the size of droplets, the overall collection efficiency and the local collection efficiencies of the slide

vary considerably with droplet size. The droplet-size distribution for any given area of the slide must be corrected according to the local collection efficiencies in order to obtain the true droplet-size distribution of the cloud. The local collection efficiencies used for this correction are based upon that of a ribbon in ideal two-dimensional flow. The exposure time required in order not to saturate the slide with droplets must be of the order of a fraction of a second. This presents some difficulties, in that the slide must be moved rapidly or a protective cover must be opened and closed rapidly. This motion disturbs the airflow field in the vicinity of the slide, and therefore the collection efficiencies of the slide are not the same as for a ribbon in ideal flow.

An oil-stream aeroscope composed of five main parts (fig. 36) - droplet pickup probe, circulating pumps for oil and air, photographic cell, light source, and a photomicrographic camera - has been developed. The droplet pickup probe consists of a small-diameter tube with a small hole on one side. When operating, the probe is arranged so that the small hole faces upstream to the air flow carrying the cloud droplets. Oil is forced by a pump through the pickup probe in the direction indicated in the sketch. As the oil passes the small hole, any water droplets that enter are trapped in the oil. Oil does not flow out of the droplet pickup hole, because the oil pressure is maintained at atmospheric pressure by the air pump shown in figure 36. The oil containing the droplets then flows through the transparent plastic cell where the droplets are photographed with a photomicrographic camera. The channel through the plastic cell narrows down at the point where the pictures are taken, so that all the droplets are approximately in the object plane of the camera. After leaving the plastic cell, the oil passes through a filter and trap where the water droplets are removed. The droplet size and distribution can then be determined by measuring the images on the photographs from the known magnification. After the droplet distribution is known, the liquid-water content of the cloud can be calculated from the known geometery of the instrument, the airspeed, and the oil-flow rate. Limited data indicate that this instrument shows excellent promise for obtaining the desired information.

The heated-wire instrument consists basically of a loop of resistance wire (refs. 39 and 40) which is mounted in the airstream (fig. 37) and is heated electrically by passing current through the wire. The wire diameter is 0.021 to 0.064 inch, with a maximum power input of 31 to 300 watts, respectively (ref. 40). The change in wire resistance from the clear-air condition, resulting from cooling due to evaporation of impinging cloud water droplets, is used as a measure of the liquid-water content, or icing severity. Although the heated-wire instrument has several disadvantages as pointed out in reference 40, a workable instrument can be obtained that is very useful in studying cloud microstructure.

A variation of the heated-wire instrument is currently under development at the NACA Lewis laboratory. This instrument consists of a heated

tube operating at constant surface temperature with a variable power input. This instrument has the following advantages over a constant-power heated-wire probe:

(1) The measured change in required power is linear with water impingement, because the surface temperature is fixed.
(2) The change of heat-transfer coefficient under all conditions is minimized.
(3) The sensitivity to water impingement is maximized.
(4) The power input is easily measured.
(5) With proper design, the time constant is less than that of a wire heated with constant power.

While the control circuit for this probe has proved formidable, a satisfactory unit has been designed and operated. The probe is currently being calibrated in the Lewis icing tunnel.

REFERENCES

1. Hacker, Paul T., and Dorsch, Robert G.: A Summary of Meteorological Conditions Associated with Aircraft Icing and a Proposed Method of Selecting Design Criterions for Ice-Protection Equipment. NACA TN 2569, 1951.

2. Lewis, William, and Bergrun, Norman R.: A Probability Analysis of the Meteorological Factors Conducive to Aircraft Icing in the United States. NACA TN 2738, 1952.

3. Jones, Alun R., and Lewis, William: Recommended Values of Meteorological Factors to be Considered in the Design of Aircraft Ice-Prevention Equipment. NACA TN 1855, 1949.

4. Lewis, William, Perkins, Porter J., and Brun, Rinaldo J.: Procedure for Measuring Liquid-Water Content and Droplet Sizes in Supercooled Clouds by Rotating Multicylinder Method. NACA RM E53D23, 1953.

5. Perkins, Porter J., McCullough, Stuart, and Lewis, Ralph D.: A Simplified Instrument for Recording and Indicating Frequency and Intensity of Icing Conditions Encountered in Flight. NACA RM E51E16, 1951.

6. Brun, Rinaldo J., Gallagher, Helen M., and Vogt, Dorothea E.: Impingement of Water Droplets on NACA 65A004 Airfoil and Effect of Change in Airfoil Thickness from 12 to 4 Percent at 4° Angle of Attack. NACA TN 3047, 1953.

7. Brun, Rinaldo J., Gallagher, Helen M., and Vogt, Dorothea E.: Impingement of Water Droplets on NACA 65_1-208 and 65_1-212 Airfoils at 4° Angle of Attack. NACA TN 2952, 1953.

8. Guibert, A. G., Janssen, E., and Robbins, W. M.: Determination of Rate, Area, and Distribution of Impingement of Waterdrops on Various Airfoils from Trajectories Obtained on the Differential Analyzer. NACA RM 9A05, 1949.

9. Brun, Rinaldo J., Gallagher, Helen M., and Vogt, Dorothea E.: Impingement of Water Droplets on NACA 65A004 Airfoil at 8° Angle of Attack. NACA TN 3155, 1954.

10. Brun, Rinaldo J., Serafini, John S., and Gallagher, Helen M.: Impingement of Cloud Droplets on Aerodynamic Bodies as Affected by Compressibility of Air Flow Around the Body. NACA TN 2903, 1953.

11. Dorsch, Robert G., and Brun, Rinaldo J.: A Method for Determining Cloud-Droplet Impingement on Swept Wings. NACA TN 2931, 1953.

12. Brun, Rinaldo J., and Dorsch, Robert G.: Impingement of Water Droplets on an Ellipsoid with Fineness Ratio 10 in Axisymmetric Flow. NACA TN 3147, 1954.

13. Dorsch, Robert G., Brun, Rinaldo J., and Gregg, John L.: Impingement of Water Droplets on an Ellipsoid with Fineness Ratio 5 in Axisymmetric Flow. NACA TN 3099, 1954.

14. Brun, Rinaldo J., and Mergler, Harry W.: Impingement of Water Droplets on a Cylinder in an Incompressible Flow Field and Evaluation of Rotating Multicylinder Method for Measurement of Droplet-Size Distribution, Volume-Median Droplet Size, and Liquid-Water Content in Clouds. NACA TN 2904, 1953.

15. von Glahn, Uwe H., Gelder, Thomas F., and Smyers, William H., Jr.: A Dye-Tracer Technique for Experimentally Obtaining Impingement Characteristics of Arbitrary Bodies and a Method for Determining Droplet Size Distribution. NACA TN 3338, 1955.

16. Sherman, P., Klein, J. S., and Tribus, M.: Determination of Drop Trajectories by Means of an Extension of Stokes' Law. Eng. Res. Inst., Univ. Mich., Apr. 1952. (Air Res. and Dev. Command, USAF, Contract AF 18(600)-51, Proj. M992-D.)

17. von Glahn, Uwe H., and Gray, Vernon H.: Effect of Ice Formations on Section Drag of Swept NACA 63A-009 Airfoil with Partial-Span Leading-Edge Slat for Various Modes of Thermal Ice Protection. NACA RM E53J30, 1954.

18. Gray, Vernon H., and von Glahn, Uwe E.: Effect of Ice and Frost Formations on Drag of NACA 65_1-212 Airfoil for Various Modes of Thermal Ice Protection. NACA TN 2962, 1953.

19. Lewis, James P., and Blade, Robert J.: Experimental Investigation of Radome Icing and Icing Protection. NACA TM E52J31, 1953.

20. Neel, Carr B., Jr., Bergrun, Norman R., Jukoff, David, and Schlaff, Bernard A.: The Calculation of the Heat Required for Wing Thermal Ice Prevention in Specified Icing Conditions. NACA TN 1472, 1947.

21. Gelder, Thomas F., and Lewis, James P.: Comparison of Heat Transfer from Airfoil in Natural and Simulated Icing Conditions. NACA TN 2480, 1951.

22. von Glahn, U.: Preliminary Results of Heat Transfer from a Stationary and Rotating Ellipsoidal Spinner. NACA RM E53F02, 1953.

23. Gelder, Thomas F., Lewis, James P., and Koutz, Stanley L.: Icing Protection for a Turbojet Transport Airplane: Heating Requirements, Methods of Protection, and Performance Penalties. NACA TN 2866, 1953.

24. Hardy, J. K.: Kinetic Temperature of Wet Surfaces - A Method of Calculating the Amount of Alcohol Required to Prevent Ice, and the Derivation of the Psychrometric Equation. NACA WR A-8, 1945. (Supersedes NACA ARR 5G13.)

25. Hardy, J. K.: An Analysis of the Dissipation of Heat in Conditions of Icing from a Section of the Wing of the C-46 Airplane. NACA Rep. 831, 1945. (Supersedes NACA ARR 4I11a.)

26. Gray, V. H., Bowden, D. T., and von Glahn, U.: Preliminary Results of Cyclical De-Icing of a Gas-Heated Airfoil. NACA RM E51J29, 1952.

27. Gray, Vernon H., and Bowden, Dean T.: Comparison of Several Methods of Cylical De-Icing of a Gas-Heated Airfoil. NACA RM E53C27, 1953.

28. Lewis, James P., and Bowden, Dean T.: Preliminary Investigation of Cyclic De-Icing of an Airfoil Using an External Electric Heater. NACA RM E51J30, 1952.

29. Coles, Willard D., and Ruggeri, Robert S.: Experimental Investigation of Sublimation of Ice at Subsonic and Supersonic Speeds and Its Relation to Heat Transfer. NACA TN 3104, 1954.

30. Coles, Willard, Rollin, Vern G., and Mulholland, Donald R.: Icing-Protection Requirements for Reciprocating-Engine Induction Systems. NACA Rep. 982, 1950. (Supersedes NACA TN 1993.)

31. Acker, Loren W.: Natural Icing of an Axial-Flow Turbojet Engine in Flight for a Single Icing Condition. NACA RM E8F01a, 1948.

32. Acker, Loren W.: Preliminary Results of Natural Icing of an Axial-Flow Turbojet Engine. NACA RM E8C18, 1948.

33. Gray, Vernon H., and Bowden, Dean T.: Icing Characteristics and Anti-Icing Heat Requirements for Hollow and Internally Modified Gas-Heated Inlet Guide Vanes. NACA RM E50I08, 1950.

34. Callaghan, Edmund E., and Serafini, John S.: A Method for Rapid Determination of the Icing Limit of a Body in Terms of the Stream Conditions. NACA TN 2914, 1953.

35. Callaghan, Edmund E., and Serafini, John S.: Analytical Investigation of Icing Limit for Diamond-Shaped Airfoil in Transonic and Supersonic Flow. NACA TN 2861, 1953.

36. Coles, Willard D.: Icing Limit and Wet-Surface Temperature Variation for Two Airfoil Shapes under Simulated High-Speed Flight Conditions. NACA TN 3396, 1955.

37. Langmuir, Irving, and Blodgett, Katherine B.: A Mathematical Investigation of Water Droplet Trajectories. Tech. Rep. No. 5418, Air Materiel Command, AAF, Feb. 19, 1946. (Contract No. W-33-038-ac-9151 with General Electric Co.)

38. McCullough, Stuart, and Perkins, Porter J.: Flight Camera for Photographing Cloud Droplets in Natural Suspension in the Atmosphere. NACA RM E50K01a, 1951.

39. Neel, Carr B., Jr., and Steinmetz, Charles P.: The Calculated and Measured Performance Characteristics of a Heated-Wire Liquid-Water-Content Meter for Measuring Icing Severity. NACA TN 2615, 1952.

40. Neel, Carr B.: A Heated-Wire Liquid-Water Content Instrument and Results of Initial Flight Test in Icing Conditions. NACA RM A54I23, 1955.

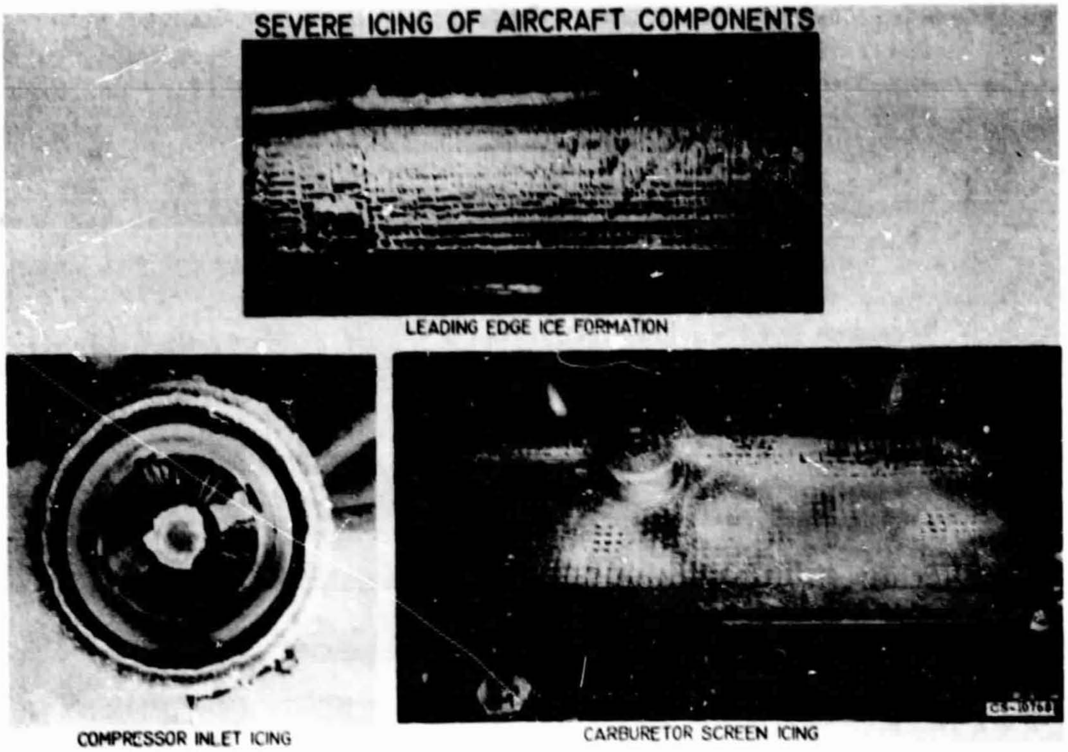
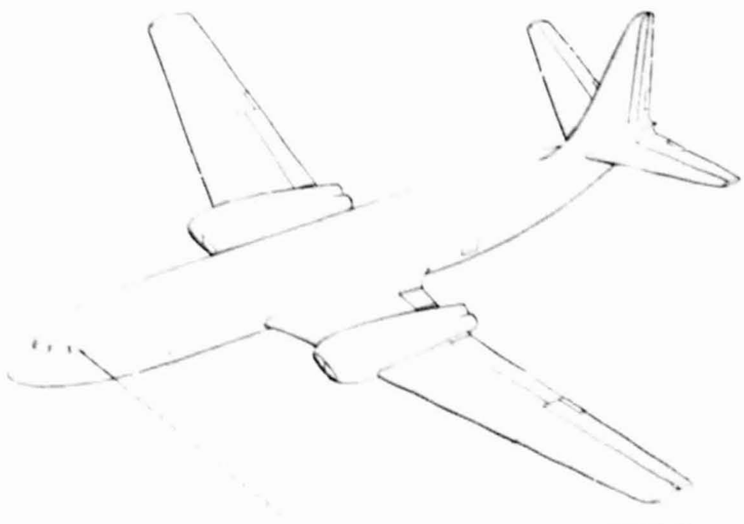


Figure 1.

AIRCRAFT SURFACES REQUIRING ICING PROTECTION



SHADING INDICATES AREAS
SUBJECT TO ICING

Figure 2.

ORIGINAL PAGE IS OF POOR QUALITY

DROPLET TRAJECTORIES ABOUT AIRFOIL

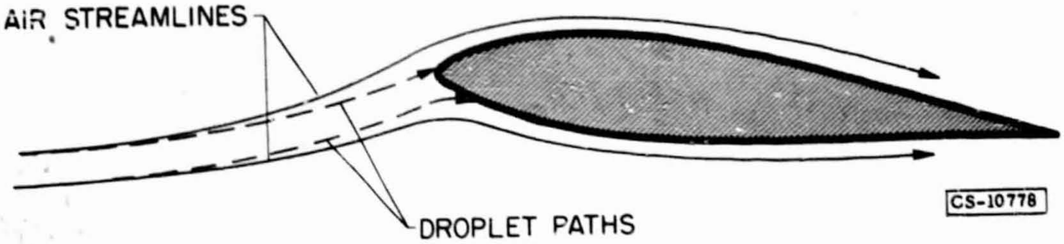


Figure 3.

MULTI-CYLINDERS INSTALLED ON AIRCRAFT

Figure 4.

PRESSURE-TYPE ICING RATE METER

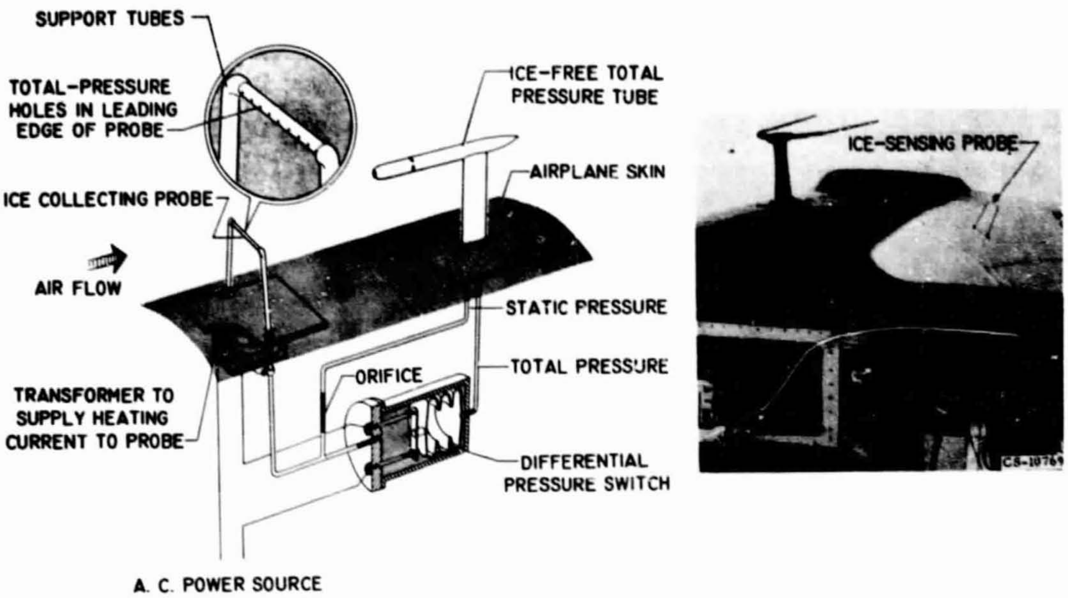


Figure 5.

WORLD ICING SURVEY ROUTES

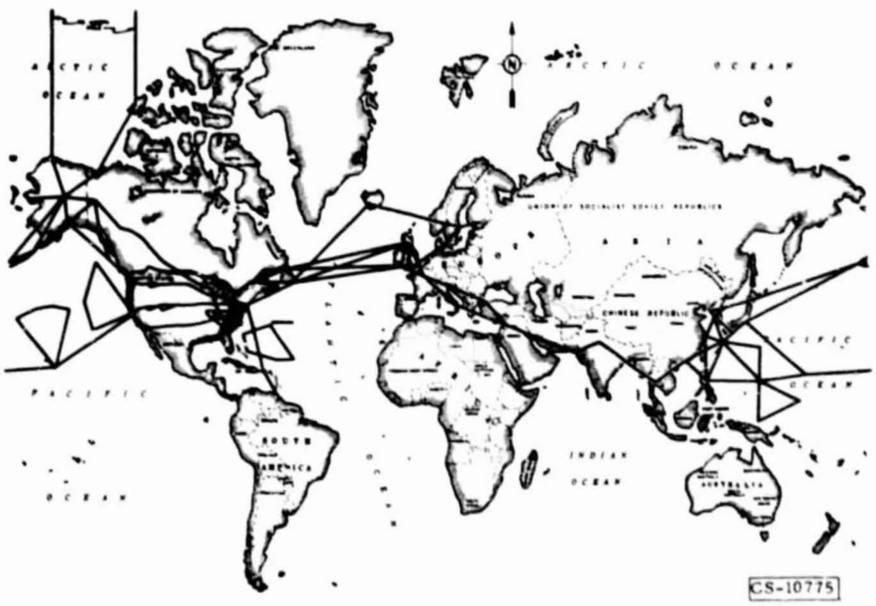


Figure 6.

WATER-DROPLET-TRAJECTORY ANALOG

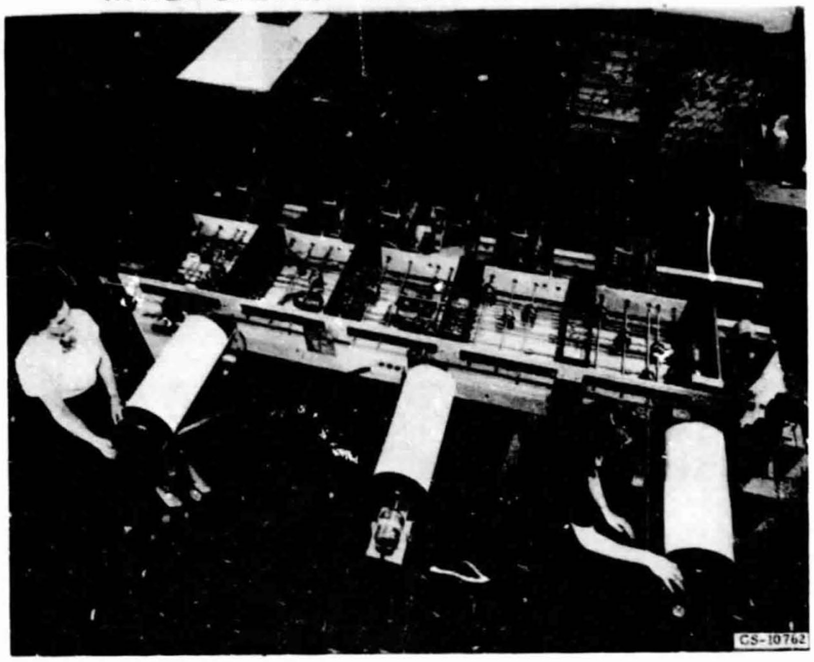


Figure 7.

LOCAL IMPINGEMENT RATES ON A 15-PERCENT THICK SYMMETRICAL AIRFOIL

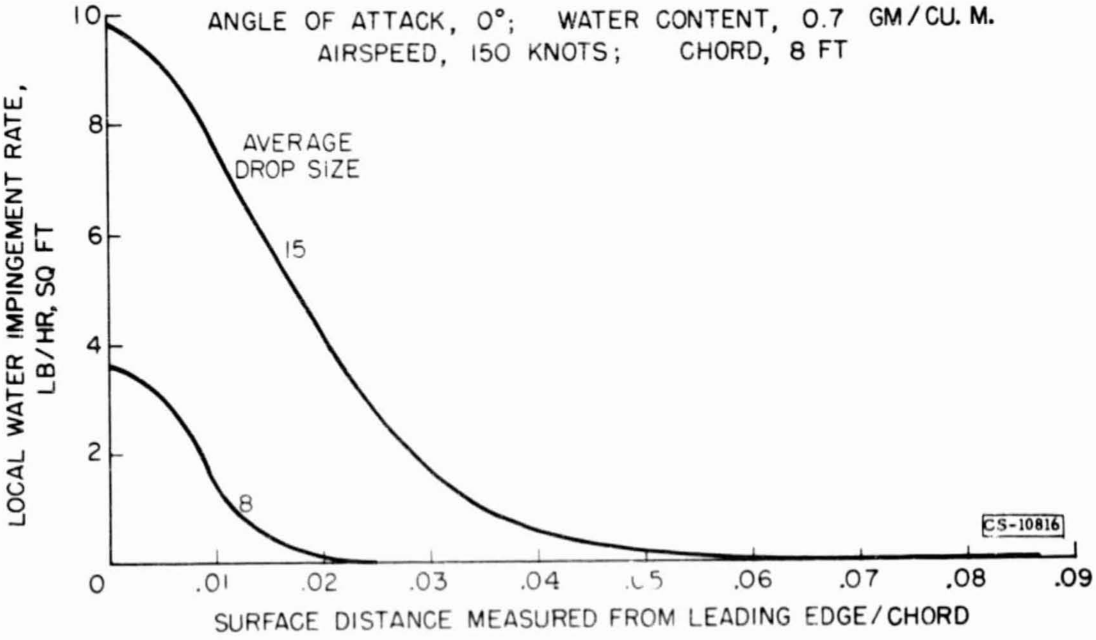


Figure 8.

MODEL USED IN OBTAINING EXPERIMENTAL IMPINGEMENT DATA

Figure 9.

COMPARISON OF THEORETICAL AND EXPERIMENTAL IMPINGEMENT DATA

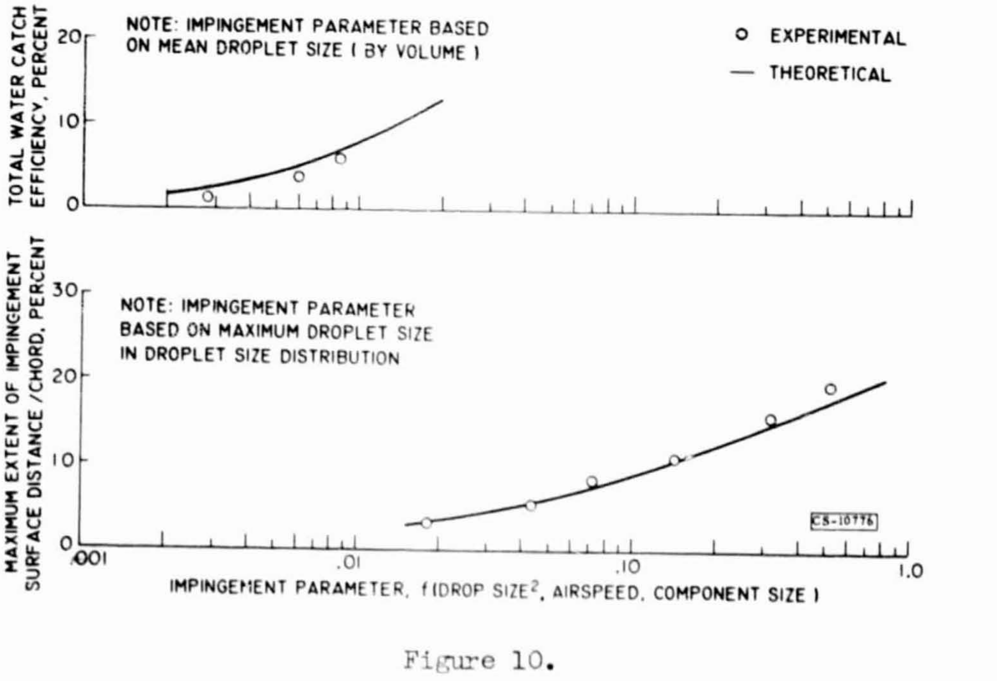
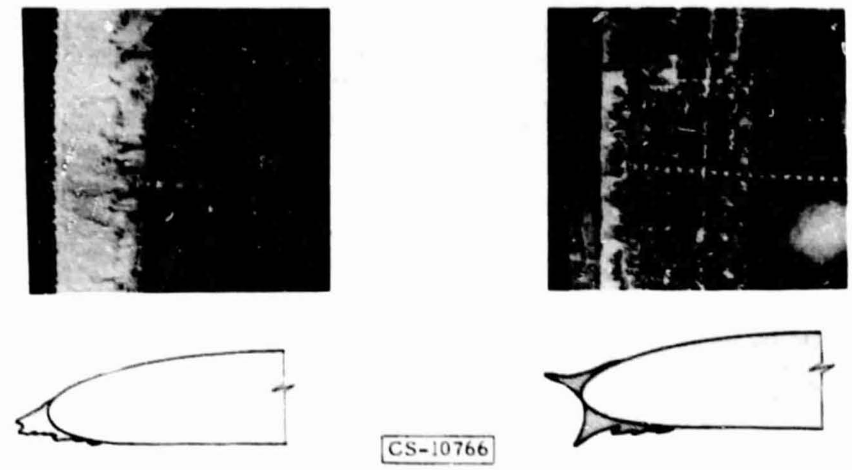


Figure 10.

TYPICAL AIRFOIL ICE FORMATIONS



(A) RIME ICE. DATUM AIR TEMPERATURE, 0° F

(B) DOUBLE PEAK GLAZE ICE. DATUM AIR TEMPERATURE, 30° F. HIGH RATE OF WATER CATCH

Figure 11.

PLAN VIEW OF ICING TUNNEL

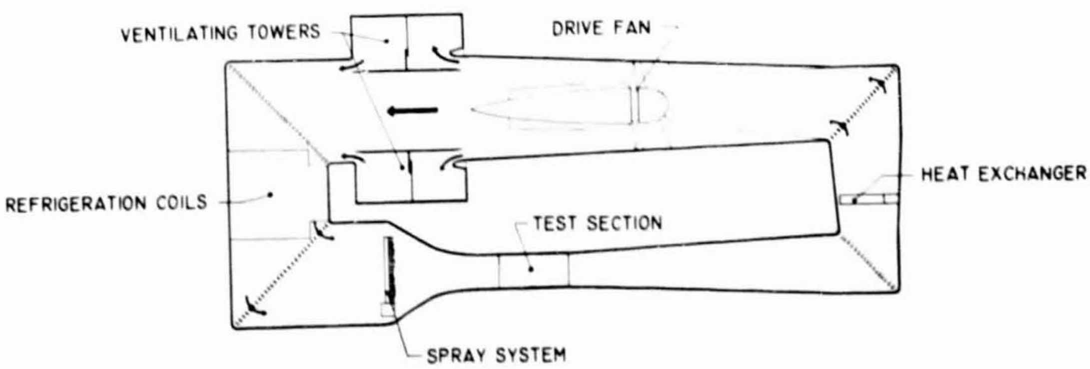


Figure 12.

ICING TUNNEL SPRAY SYSTEM

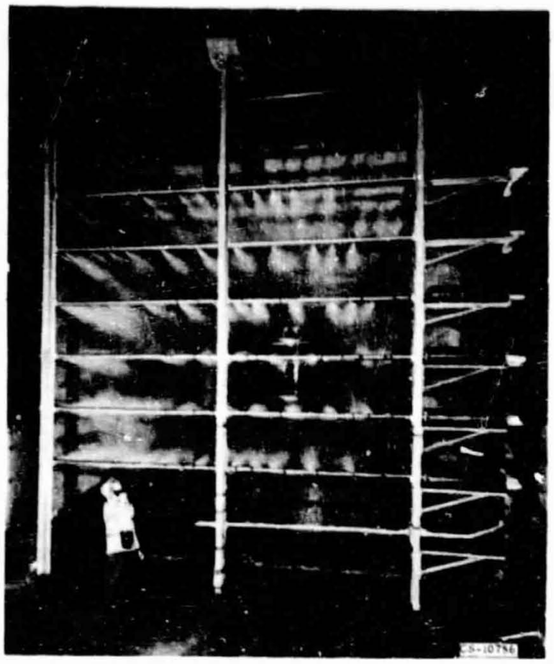


Figure 13.

MODEL USED TO STUDY AERODYMAMIC PENALTIES
CAUSED BY ICING

Figure 14.

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CHANGES IN LIFT AND DRAG CAUSED BY ICING

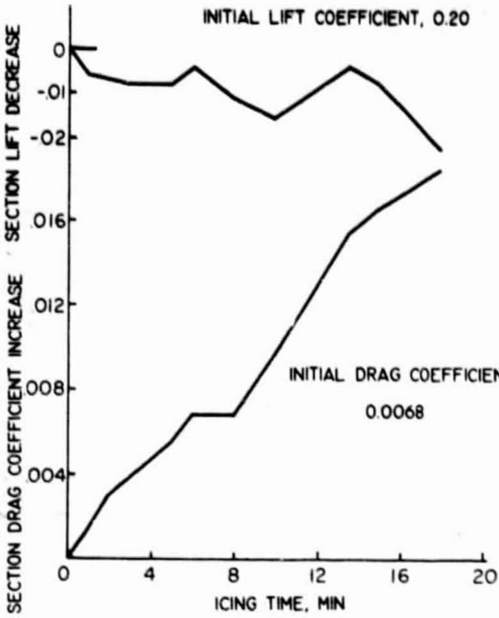


Figure 15.

TYPICAL HEAT LOSSES ASSOCIATED WITH ANTI-ICING

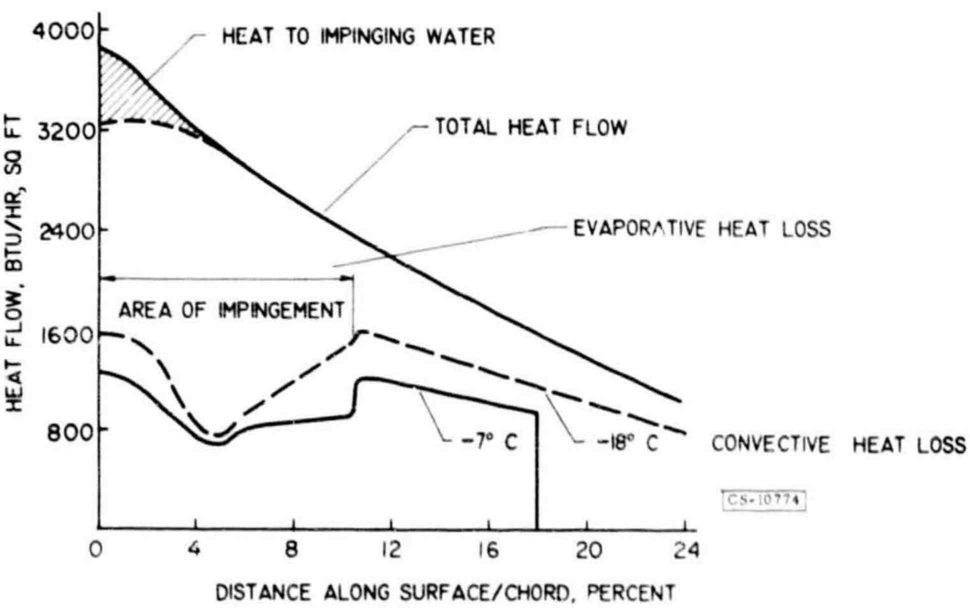


Figure 16.

C-46 AIRCRAFT WITH THERMALLY ANTI-ICED AIRFOIL MODEL

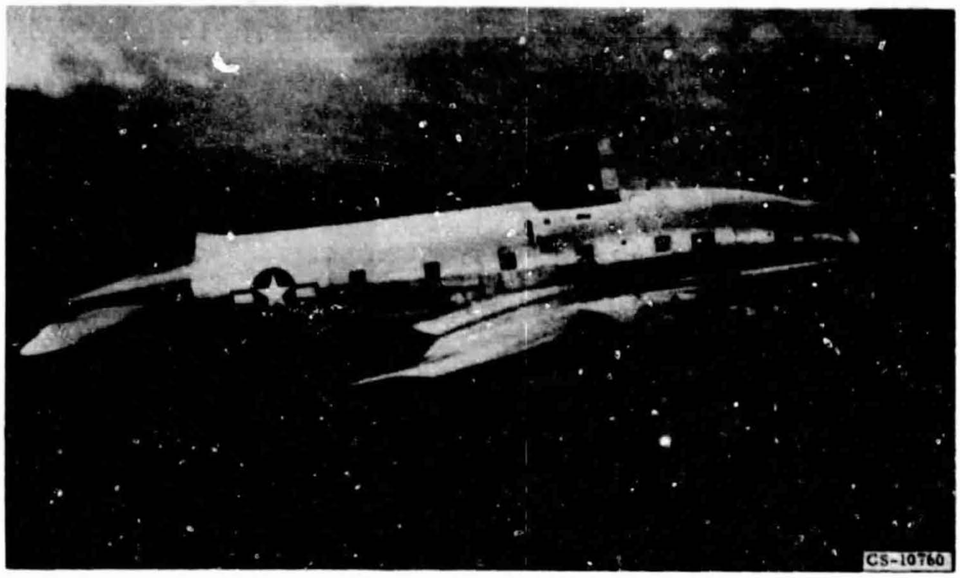


Figure 17.

TYPICAL ELECTRIC HEATER CONSTRUCTION FOR C-46 FLIGHT STUDIES

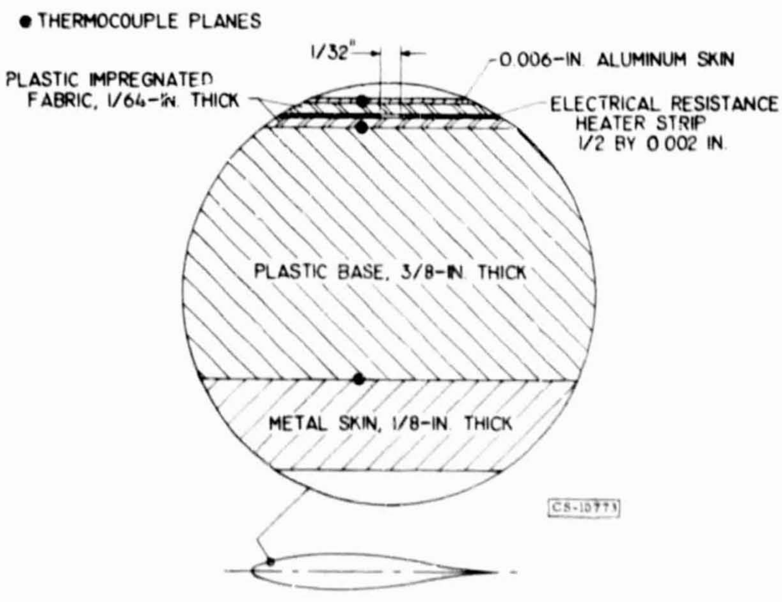


Figure 18.

NACA AIR HEATED CYCLICALLY DE-ICING WING

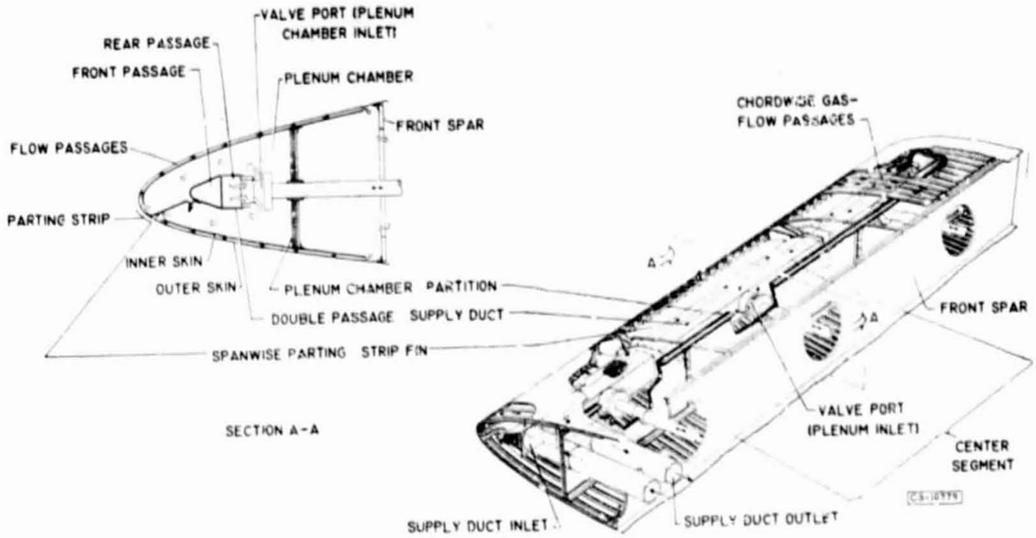
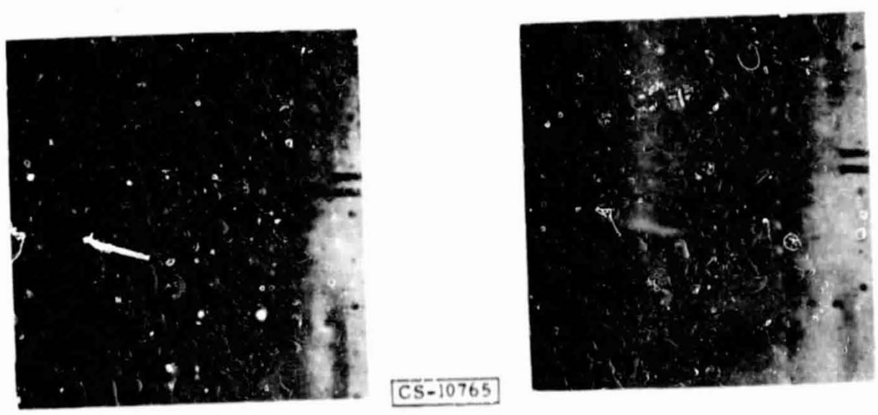


Figure 19.

ICE FORMATIONS ON AIRFOIL BEFORE AND AFTER CYCLIC HEATING



(A) BEFORE HEAT-ON PERIOD (B) AFTER 15-SECOND HEAT-ON PERIOD

Figure 20.

PNEUMATIC BOOT DE-ICING SYSTEM

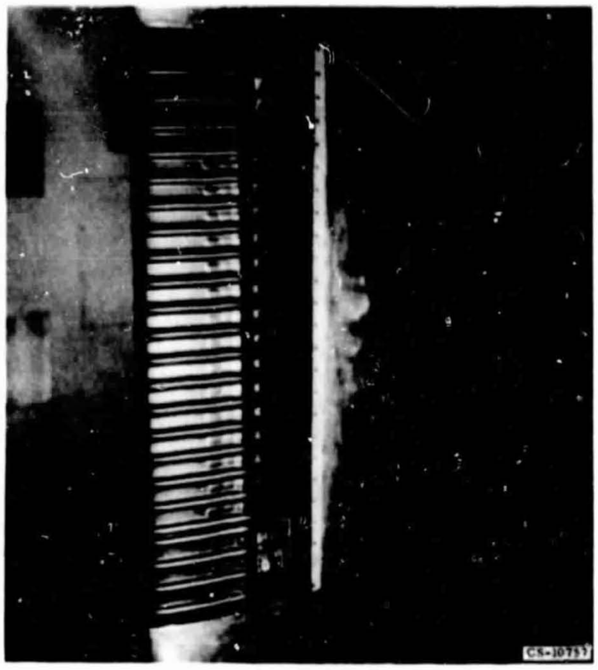


Figure 21

ICING PROTECTION FOR PISTON ENGINE-INDUCTION SYSTEM

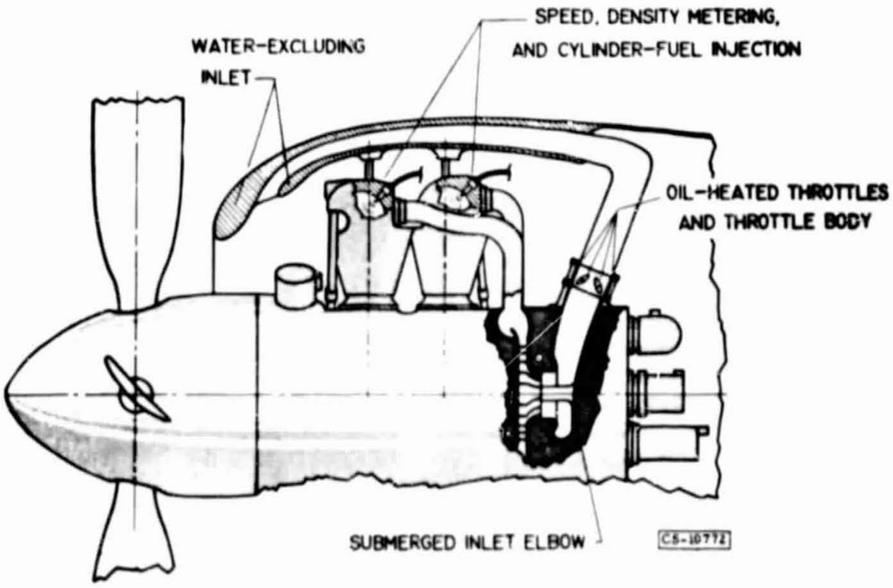


Figure 22.

TYPICAL ICING OF JET ENGINE INLET

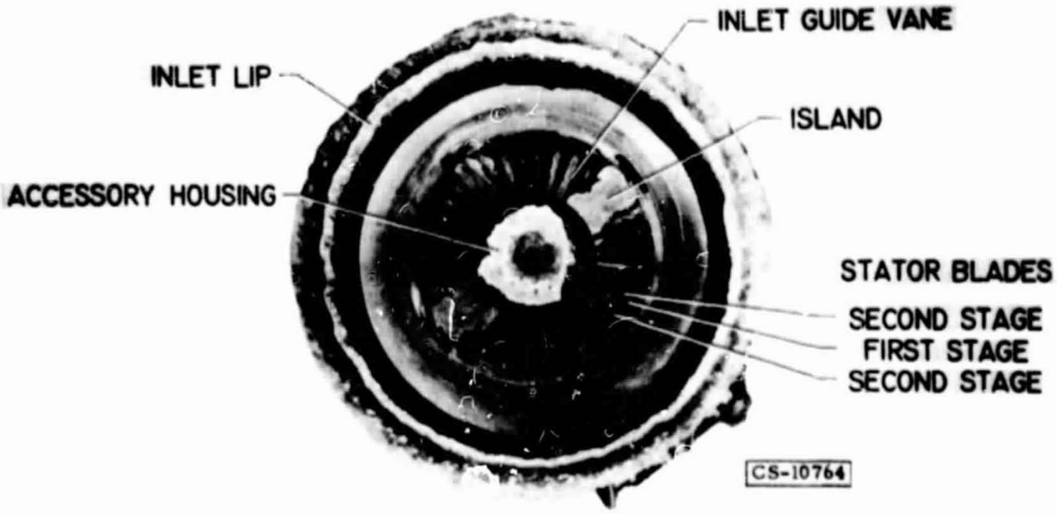


Figure 23.

MODEL USED IN GUIDE VANE STUDIES

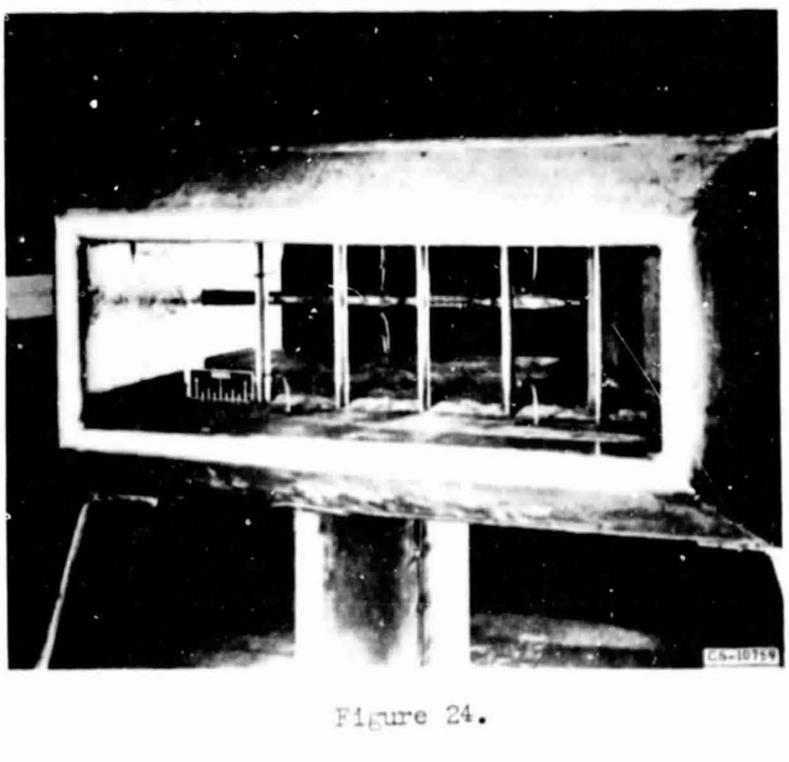


Figure 24.

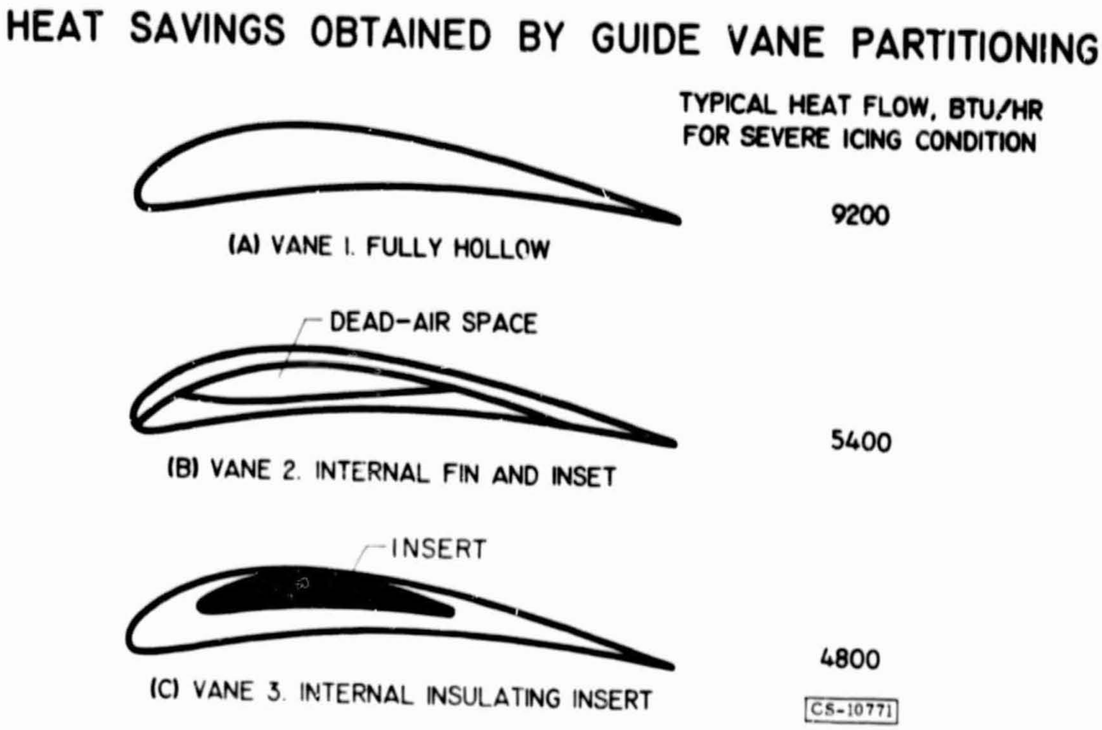


Figure 25.

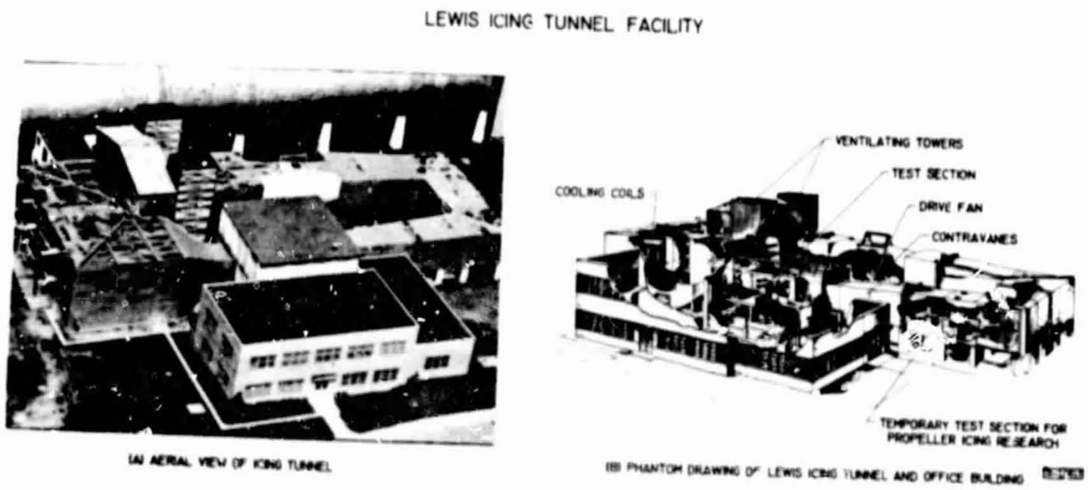


Figure 26.

CROSS SECTION OF NACA AIR-WATER ATOMIZING SPRAY NOZZLE

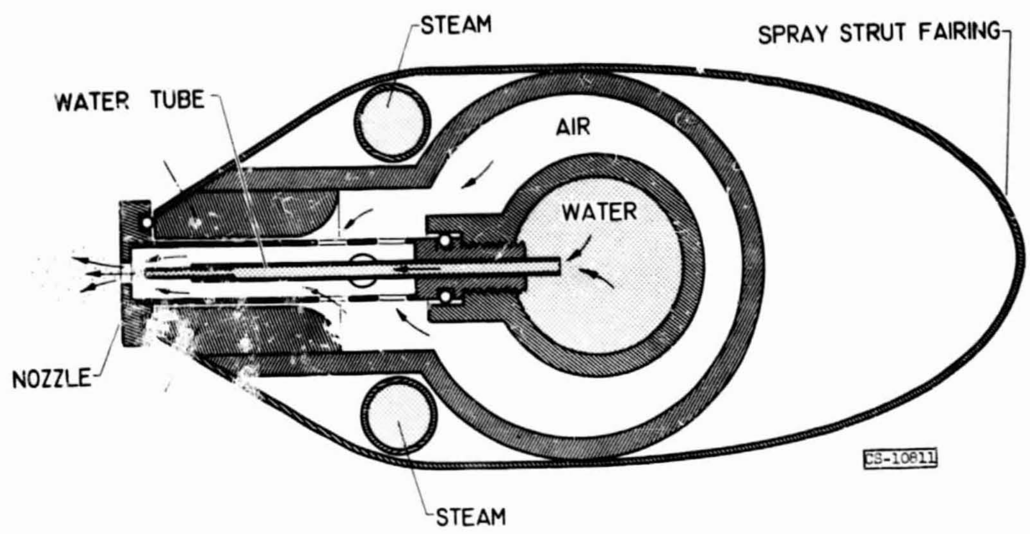


Figure 27.

NACA 3.84x10-INCH HIGH-SPEED ICING DUCT TUNNEL

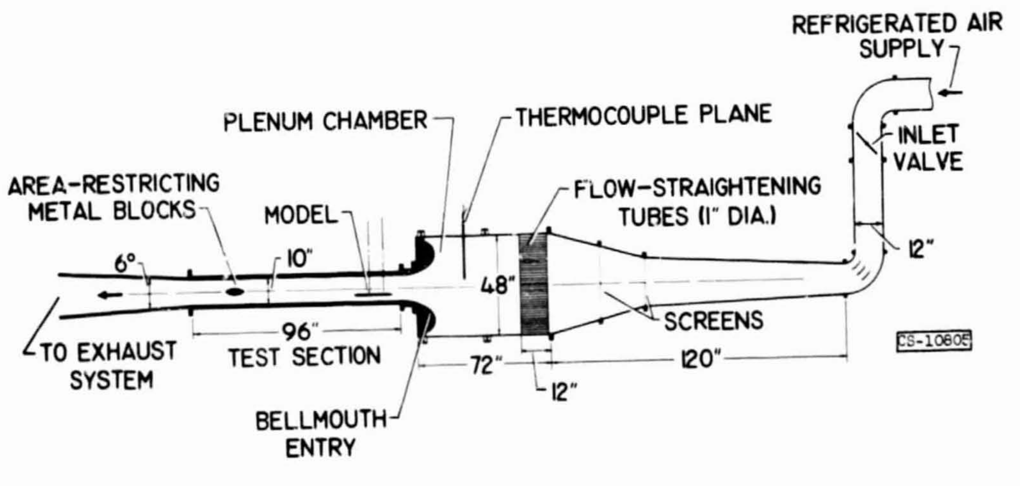


Figure 28.

NACA 12 x 12-INCH HIGH-SPEED ICING DUCT TUNNEL

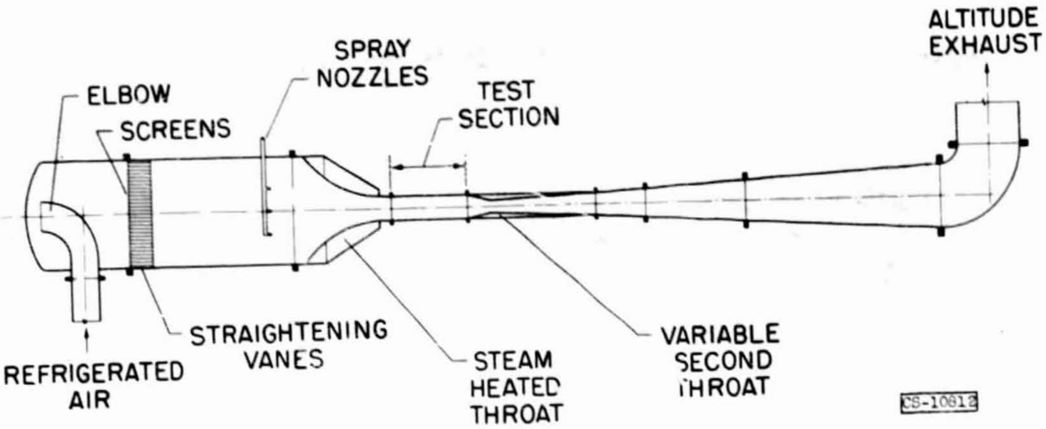


Figure 29.

THERMOCOUPLE INSTALLATION DETAILS

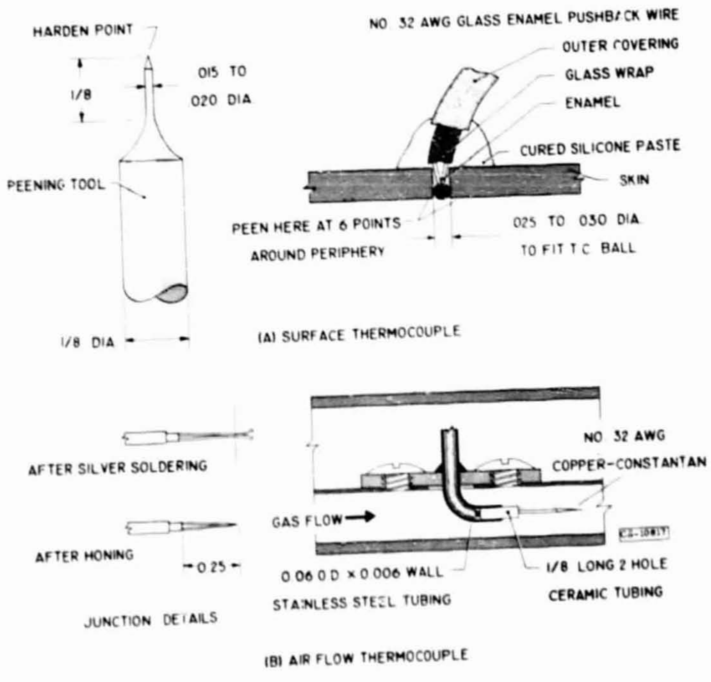


Figure 30.

INERTIA-SEPARATION TEMPERATURE PROBE

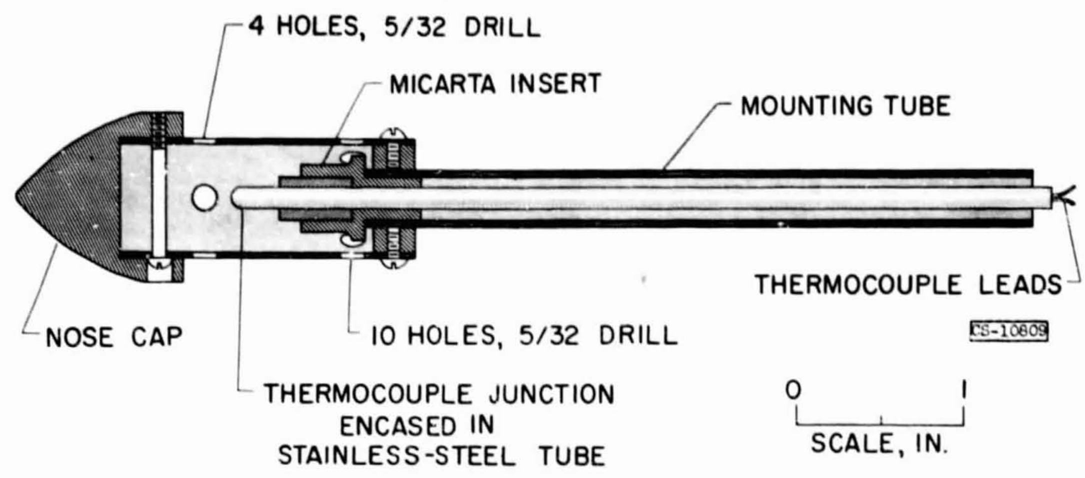


Figure 31

SCHEMATIC DIAGRAM FOR TEMPERATURE MEASURING SYSTEM ON ROTATING BODIES

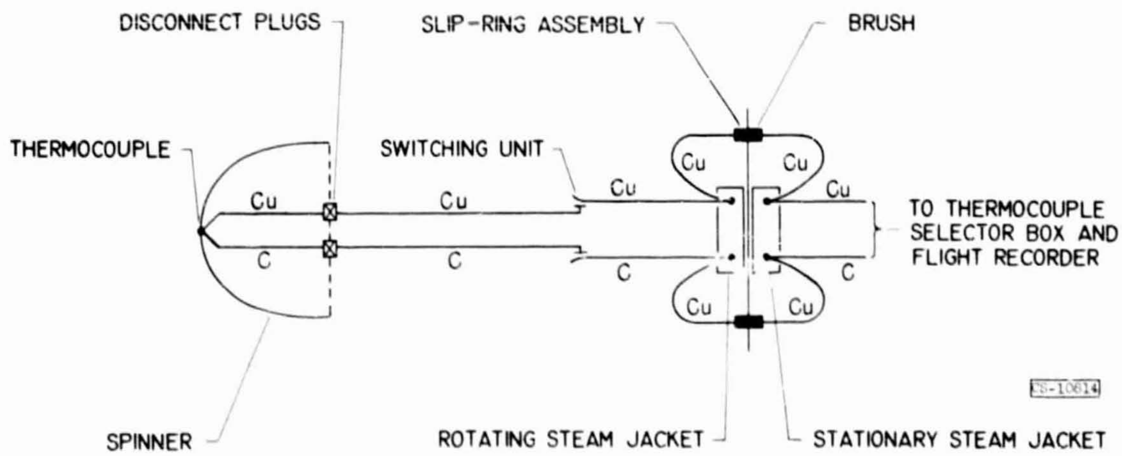


Figure 32

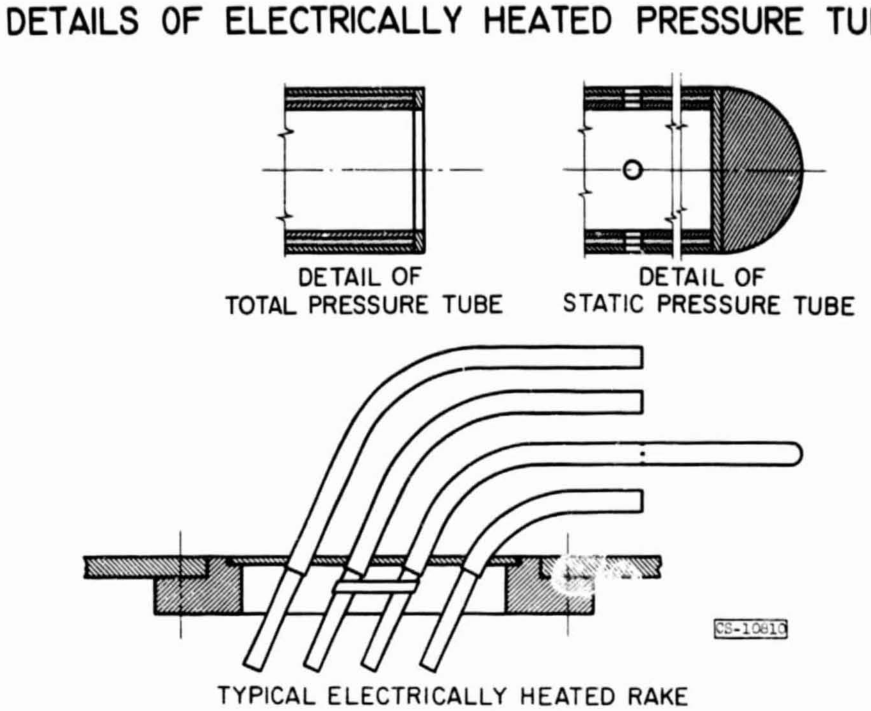


Figure 33

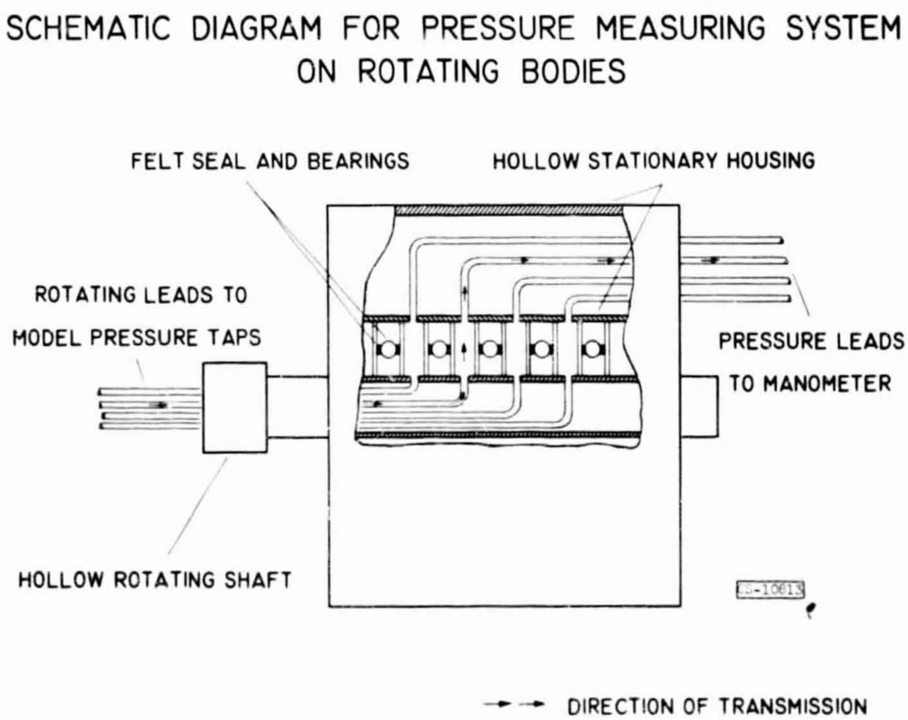


Figure 34

NACA CLOUD CAMERA

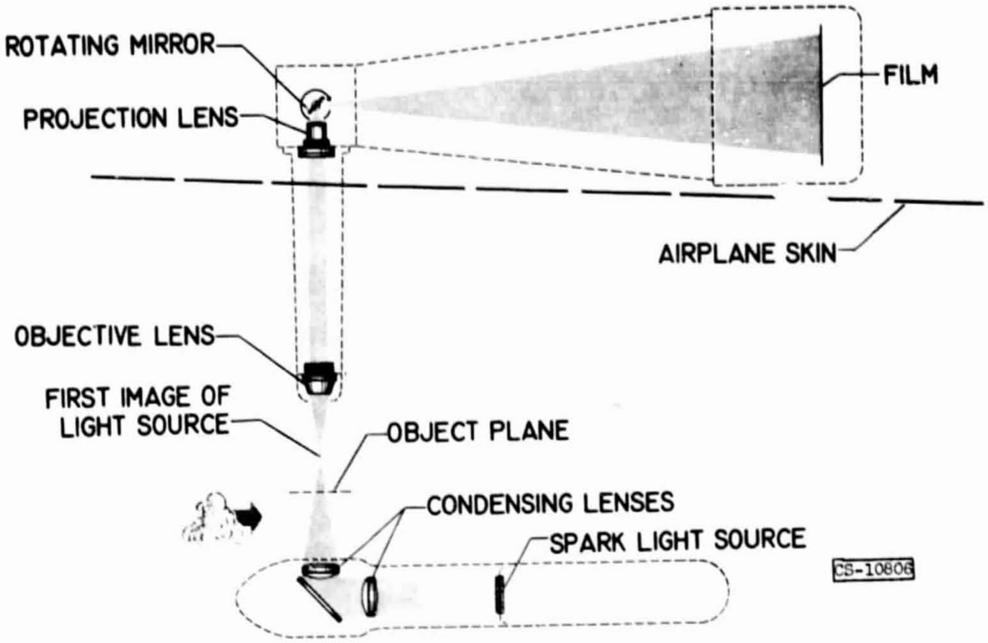


Figure 35

SCHEMATIC SKETCH OF OIL-STREAM AEROSCOPE

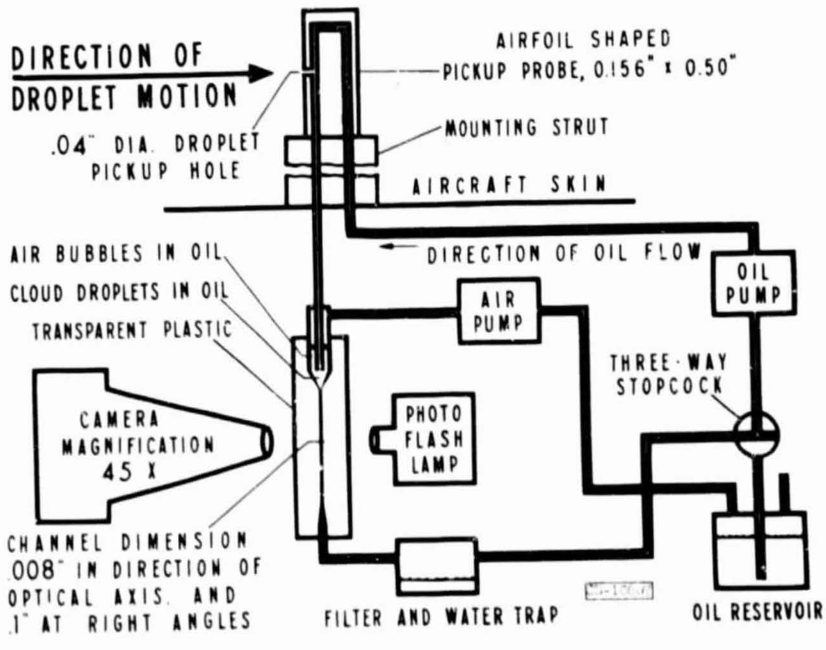
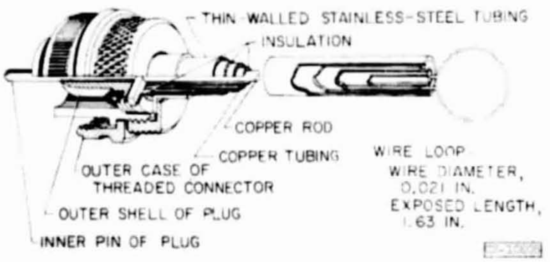


Figure 36

HOT WIRE LIQUID WATER CONTENT METER

(A) WIRE-LOOP AND SUPPORTING-STRUT ASSEMBLY



(B) CONSTRUCTION DETAILS OF WIRE-LOOP ASSEMBLY AND SUPPORTING-STRUT ASSEMBLY

Figure 37

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SELECTED BIBLIOGRAPHY OF

NACA-NASA AIRCRAFT ICING PUBLICATIONS

Meteorology of Icing Clouds

1. N81-73269 Bergrun, N.R. and Lewis, Wm.: A Probability Analysis of the Meteorological Factors Conducive to Aircraft Icing in the United States. NACA TN 2738, 1952.

2. N81-73270 Hacker, P.T. and Dorsch, R.G.: A Summary of Meteorological Conditions Associated with Aircraft Icing and a Proposed Method of Selecting Design Criterions for Ice Protection Equipment. NACA TN 2569, 1951.

3. N81-73271 Jones, A.R. and Lewis, Wm.: Recommended Values of Meteorological Factors to be Considered in the Design of Aircraft Ice Prevention Equipment. NACA TN 1855, 1949.

4. N81-73272 Kline, D.B.: Investigation of Meteorological Conditions Associated with Aircraft Icing in Layer-Type Clouds for 1947-48 Winter. NACA TN 1793, 1949.

5. N81-73273 Kline, D.B. and Walker, J.A.: Meteorological Analysis of Icing Conditions Encountered in Low-Altitude Stratiform Clouds. NACA TN 2306, 1951.

6. N81-73274 Lewis, Wm.: Icing Properties of Non-Cyclonic Winter Stratus Clouds. NACA TN 1391, 1947.

7. N81-73275 Lewis, Wm. and Hoecker, W.H., Jr.: Observations of Icing Conditions Encountered in Flight During 1948. NACA TN 1904, 1949.

8. N81-73276 Lewis, Wm., Kline, W.B. and Steinmetz, C.P.: A Further Investigation of the Meteorological Conditions Conducive to Aircraft Icing. NACA TN 1424, 1947.

9. N81-73277 Perkins, P.J.: Preliminary Survey of Icing Conditions Measured During Routine Transcontinental Airline Operation. NACA RM E52J06, 1952.

10. N81-73278 Perkins, P.J.: Statistical Survey of Icing Data Measured on Scheduled Airline Flights over the United States and Canada. NACA RM E55F28a, 1955.

11. N81-73279 Perkins, P.J.: Icing Frequencies Experienced During Climb and Descent by Fighter-Interceptor Aircraft. NACA TN 4314, 1958.

12. Perkins, P.J. and Kline, D.B.: Analysis of Meteorological Data
N81-73280 Obtained During Flight in a Supercooled Stratiform Cloud of High Liquid Water Content. NACA RM E51D18, 1951.

13. Perkins, P.J., Lewis, W. and Mulholland, D.R.: Statistical Study of
N81-73281 Aircraft Icing Probabilities at the 700- and 500-Millibar Levels over Ocean Areas in the Northern Hemisphere. NACA TN 3984, 1957.

14. Perkins, P.J.: Summary of Statistical Icing Cloud Data Measured Over
N81-73282 United States and North Atlantic, Pacific, and Arctic Oceans During Routine Aircraft Operations. NASA Memo 1-19-59E, 1959.

Fundamental Properties of Water

15. Levine, J.: Statistical Explanation of Spontaneous Freezing of Water
N81-73283 Droplets. NACA TN 2234, 1950.

16. Dorsch, R.G., and Hacker, P.T.: Photomicrographic Investigation of
N81-73284 Spontaneous Freezing Temperatures of Supercooled Water Droplets. NACA TN 2142, 1950.

17. Hacker, P.T.: Experimental Values of the Surface Tension of
N81-73285 Supercooled Water. NACA TN 2510, 1951.

18. Dorsch, R.G., and Boyd, B.: X-Ray Diffraction Study of the Internal
N81-73065 Structure of Supercooled Water. NACA TN 2532, 1951.

19. Dorsch, R.G., and Levine, J.: A Photographic Study of Freezing of
N81-73286 Water Droplets Falling Freely in Air. NACA RM E51L17, 1952.

20. Lowell, H.H.: Maximum Evaporation Rates of Water Droplets Approaching
N81-73287 Obstacles in the Atmosphere. NACA TN 3024, 1953.

21. Hardy, J.K.: Kinetic Temperature of Wet Surfaces. A Method of
N81-73321 Calculating the Amount of Alcohol Required to Prevent Ice, and the Derivation of the Psychometric Equation. ARC R&M 2830, 1953. NACA ARR 5G13, 1945. See also WR A-8.

Meteorological Instruments

22. Neel, C.B., Jr. and Steinmetz, C.P.: The Calculated and Measured
N81-73149 Performance Characteristics of a Heated-Wire Liquid-Water-Content Meter for Measuring Icing Severity. NACA TN 2615, 1952.

23. Lewis, Wm., Perkins, P.J., and Brun, R.J.: Procedure for Measuring
N81-73322 Liquid-Water Content and Droplet Sizes in Supercooled Clouds by Rotating Multicylinder Method. NACA RM E53D23, 1953.

24. N81-73288 McCullough, S., and Perkins, P.J.: Flight Camera for Photographing Cloud Droplets in Natural Suspension in the Atmosphere. NACA RM E50K01a, 1951.

25. N81-73150 Perkins, P.J.: Flight Instrument for Measurement of Liquid-Water Content in Clouds at Temperatures Above and Below Freezing. NACA RM E50J12a, 1951.

26. N81-73151 Perkins, P.J., McCullough, S., and Lewis, R.D.: A Simplified Instrument for Recording and Indicating Frequency and Intensity of Icing Conditions Encountered in Flight. NACA RM E51E16, 1951.

27. N81-73152 Brun, R.J., Levine, J., and Kleinknecht, K.S.: An Instrument Employing Coronal Discharge for Determination of Droplet Size Distribution of Clouds. NACA TN 2458, 1951.

28. N81-73153 Levine, J., and Kleinknecht, K.S.: Adaptation of a Cascade Impactor to Flight Measurement of Droplet Size in Clouds. NACA RM E51G05, 1951.

29. N81-73154 Howell, W.E.: Comparison of Three Multicylinder Icing Meters and Critique of Multicylinder Method. NACA TN 2708, 1952.

30. N81-73155 Jones, A.R., and Lewis, W.: A Review of Instruments Developed for the Measurement of the Meteorological Factors Conducive to Aircraft Icing. NACA RM A9C09, 1949.

31. N81-73156 Neel, C.B.: A Heated-Wire Liquid-Water-Content Instrument and Results of Initial Flight Test in Icing Conditions. NACA RM A54I23, 1955.

32. N81-73157 Hacker, P.T.: An Oil-Stream Photomicrographic Aeroscope for Obtaining Cloud Liquid-Water Content and Droplet Size Distributions in Flight. NACA TN 3592, 1956.

Impingement of Cloud Droplets

33. N81-73099 Bergrun, N.R.: An Empirical Method Permitting Rapid Determination of the Area, Rate, and Distribution of Water-Drop Impingement on an Airfoil of Arbitrary Section at Subsonic Speeds. NACA TN 2476, 1951.

34. N81-73100 Bergrun, N.R.: A Method for Numerically Calculating the Area and Distribution of Water Impingement on the Leading Edge of an Airfoil in a Cloud. NACA TN 1397, 1947.

35. N81-73101 Brun, R.J., Serafini, J.S., and Moshos, G.J.: Impingement of Water Droplets on an NACA 651-212 Airfoil at an Angle of Attack of 4°. NACA RM E52B12, 1952.

36. Hacker, P.T., Brun, R.J., and Boyd, B.: Impingement of Droplets in
N81-73102 90° Elbows with Potential Flow, NACA TN 2999, 1953.

37. Serafini, J.S.: Impingement of Water Droplets on Wedges and Diamond
N81-73103 Airfoils at Supersonic Speeds. NACA Rep. 1159, 1954.
(Supersedes NACA TN 2971).

38. Brun, R.J., Gallagher, H.M., and Vogt, D.E.: Impingement of Water
N81-73104 Droplets on NACA 65A-004 Airfoil and Effect of Change in Airfoil
Thickness from 12 to 4 Percent at 4° Angle of Attack.
NACA TN 3047, 1953.

39. Brun, R.J., Gallagher, H.M., and Vogt, D.E.: Impingement of Water
N81-73105 Droplets on NACA 65_1-208 and 65_1-212 Airfoils at 4° Angle of Attack.
NACA TN 2952, 1953.

40. Brun, R.J., and Mergler, H.W.: Impingement of Water Droplets on
N81-73106 a Cylinder in an Incompressible Flow Field and Evaluation of Rotating
Multicylinder Method for Measurement of Droplet-Size Distribution,
Volume Median Droplet Size, and Liquid-Water Content in Clouds.
NACA TN 2904, 1953.

41. Brun, R.J., Serafini, J.S., and Gallagher, H.M.: Impingement of Cloud
N81-73107 Droplets on Aerodynamic Bodies as Affected by Compressibility of Air
Flow Around the Body. NACA TN 2903, 1953.

42. Guibert, A.G.. Janssen, E., and Robbins, W.M.: Determination of Rate,
N81-73108 Area, and Distribution of Impingement of Waterdrops on Various
Airfoils from Trajectories Obtained on the Differential Analyzer.
NACA RM 9A05, 1949.

43. Dorsch, R.G., and Brun, R.J.: A Method for Determining Cloud-Droplet
N81-73109 Impingement on Swept Wings. NACA TN 2931, 1953.

44. Brun, R.J., and Dorsch, R.G.: Impingement of Water Droplets on an
N81-73110 Ellipsoid with Fineness Ratio 10 in Axisymmetric Flow.
NACA TN 3147, 1954.

45. Dorsch, R.G., Brun, R.J., and Gregg, J.L.: Impingement of Water
N81-73111 Droplets on an Ellipsoid with Fineness Ratio 5 in Axisymmetric Flow.
NACA TN 3099, 1954.

46. Dorsch, R.G., and Brun, R.J.: Variation of Local Liquid-Water
N81-73112 Concentration about an Ellipsoid of Fineness Ratio 5 Moving in
a Droplet Field. NACA TN 3153, 1954.

47. Brun, R.J., Gallagher, H.M., and Vogt, D.E.: Impingement of Water
N81-73113 Droplets on NACA 65A004 Airfoil at 8° Angle of Attack.
NACA TN 3155, 1954.

48. Brun, R.J., and Dorsch, R.G.: Variation of Local Liquid-Water
N81-73114 Concentration about an Ellipsoid of Fineness Ratio 10 Moving in a Droplet Field. NACA TN 3410, 1955.

49. von Glahn, U., Gelder, T.F., and Smyers, W.H.: A Dye-Tracer
N81-73115 Technique for Experimentally Obtaining Impingement Characteristics of Arbitrary Bodies and a Method for Determining Droplet Size Distribution. NACA TN 3338, 1955.

50. Dorsch, R.G., Saper, P.G., and Kadow, C.F.: Impingement of Water
N81-73116 Droplets on a Sphere. NACA TN 3587, 1955.

51. Lewis, Wm., and Brun, R.J.: Impingement of Water Droplets on
N81-73117 a Rectangular Half Body in a Two-Dimensional Incompressible Flow Field. NACA TN 3658, 1956.

52. Brun, R.J., and Vogt, D.E.: Impingement of Water Droplets on
N81-73118 NACA 65A004 Airfoil at 0° Angle of Attack. NACA TN 3586, 1955.

53. Brun, R.J., Lewis, Wm., Perkins, P.J., and Serafini, J.S.:
N81-73119 Impingement of Cloud Droplets on a Cylinder and Procedure for Measuring Liquid-Water Content and Droplet Sizes in Supercooled Clouds by Rotating Multicylinder Method. NACA Rep. 1215, 1955. (Supersedes NACA TN's 2903, 2904, and NACA RM E53D23)

54. Brun, R.J.: Cloud-Droplet Ingestion in Engine Inlets with Inlet
N81-73120 Velocity Ratios of 1.0 and 0.7. NACA Report 1317 (supersedes NACA TN 3593), 1956.

55. Gelder, T.F.: Droplet Impingement and Ingestion by Supersonic
N81-73121 Nose Inlet in Subsonic Tunnel Conditions. NACA TN 4268, 1958.

56. Gelder, T.F., Smyers, W.H. and von Glahn, U.H.: Experimental
N81-73122 Droplet Impingement on Several Two-Dimensional Airfoils with Thickness Ratios of 6 to 16 Percent. NACA TN 3839, 1956.

57. Hacker, P.T., Saper, P.G. and Kadow, C.F.: Impingement of Droplets
N81-73123 in 60° Elbows with Potential Flow. NACA TN 3770, 1956.

58. Lewis, J.P. and Ruggeri, R.S.: Experimental Droplet Impingement
N81-73124 on Four Bodies of Revolution. NACA TN 4092, 1957.

59. Brun, R.J. and Vogt, D.: Impingement of Cloud Droplets on
N81-73125 36.5-Percent-Thick Joukowski Airfoil at Zero Angle of Attack and Discussion of Use as Cloud Measuring Instrument in Dye Tracer Technique. NACA TN 4035, 1957.

60. von Glahn, U.H.: Use of Truncated Flapped Airfoils for Impingement
N81-73126 and Icing Tests of Full-Scale Leading-Edge Sections.
NACA RM E56E11, 1956.

Propeller Icing Protection

61. Selna, J. and Darsow, J.F.: A Flight Investigation of the Thermal
N81-73038 Performance of an Air-Heated Propeller. NACA TN 1178, 1947.

62. Lewis, J.P., and Stevens, H.C., Jr.: Icing and De-Icing of
N81-73039 a Propeller with Internal Electric Blade Heaters.
NACA TN 1691, 1948.

63. Lewis, J.P.: De-Icing Effectiveness of External Electric Heaters
N81-73040 for Propeller Blades. NACA TN 1520, 1948.

64. Perkins, P.J., and Millenson, M.B.: An Electric Thrust Meter Suitable
N81-73158 for Flight Investigation of Propellers. NACA RM E9C17, 1949.

65. Mulholland, D.R., and Perkins, P.J.: Investigation of
N81-73041 Effectiveness of Air-Heating a Hollow Steel Propeller for Protection
Against Icing I - Unpartitioned Blades. NACA TN 1586, 1948.

66. Perkins, P.J., and Mulholland, D.R.: Investigation of Effectiveness
N81-73042 of Air-Heating a Hollow Steel Propeller for Protection Against
Icing II - 50-Percent Partitioned Blades. NACA TN 1587, 1948.

67. Mulholland, D.R., and Perkins, P.J.: Investigation of Effectiveness
N81-73043 of Air-Heating a Hollow Steel Propeller for Protection Against
Icing III - 25-Percent Partitioned Blades. NACA TN 1588, 1948.

68. Gray, V.H., and Campbell, R.G.: A Method for Estimating Heat
N81-73044 Requirements for Ice Prevention on Gas-Heated Hollow Propeller
Blades. NACA TN 1494, 1947.

69. Neel, C.B., Jr.: An Investigation Utilizing an Electrical Analogue
N81-73045 of Cyclic De-Icing of a Hollow Steel Propeller with an External Blade
Shoe. NACA TN 2852, 1952.

70. Neel, C.B., Jr. An Investigation Utilizing an Electrical Analogue
N81-73046 of Cyclic De-Icing of Hollow Steel Propellers with Internal Electric
Heaters. NACA TN 3025, 1953.

71. Bright, L.G., and Neel, C.B., Jr.: The Effect of the Ice Formations
N81-73047 on Propeller Performance. NACA TN 2212, 1950.

Induction System Icing Protection

72. Coles, W.D.: Investigation of Icing Characteristics of a Typical
N81-73048 Light-Airplane Engine Induction System. NACA TN 1790, 1949.

73. Coles, W.D., Rollin, V.G., and Mulholland, D.R.: Icing Protection
N81-73049 Requirements for Reciprocating-Engine Induction Systems.
NACA TR 982, 1950.

74. Lewis, J.P.: Investigation of Aerodynamic and Icing Characteristics
N81-73003 of a Flush Alternate-Inlet Induction-System Air Scoop.
NACA RM E53E07, 1953.

Turbine-Type Engine and Inlet Icing Studies

75. Acker, L.W.: Natural Icing of an Axial-Flow Turbojet Engine in Flight
N81-73050 for a Single Icing Condition. NACA RM E8F01a, 1948.

76. Acker, L.W.: Preliminary Results of Natural Icing of an Axial-Flow
N81-73051 Turbojet Engine. NACA RM E8C18, 1948.

77. Gray, V.H., and Bowden, D.T.: Icing Characteristics and Anti-Icing
N81-73052 Heat Requirements for Hollow and Internally Modified Gas-Heated
Inlet Guide Vanes. NACA RM E50I08, 1950.

78. Lewis, J.P. and Ruggeri, R.S.: An Investigation of Heat Transfer
N81-73127 from a Stationary and Rotating Ellipsoidal Forebody of Fineness
Ratio 3. NACA TN 3837, 1956.

79. Ruggeri, R.S. and Lewis, J.P.: Investigation of Heat Transfer
N81-73128 from a Stationary and Rotating Conical Forebody. NACA TN 4093, 1957.

80. von Glahn, U.H., and Blatz, R.E.: Investigation of Power
N81-73129 Re-Requirements for Ice Prevention and Cyclical De-Icing of Inlet
Guide Vanes with Internal Electric Heaters. NACA RM E50H29, 1950.

81. von Glahn, U.H., Callaghan, E.E. and Gray, V.H.: NACA Investigations
N81-73053 of Icing-Protection Systems for Turbojet-Engine Installation.
NACA RM E51B12, 1951.

82. Gelder, T.F.: Total Pressure Distortion and Recovery of Supersonic
N81-73004 Nose Inlet with Conical Centerbody in Subsonic Icing Conditions. NACA
RM E57G09, 1957.

83. von Glahn, U., and Blatz, R.E.: Investigation of Aerodynamic and
N81-73054 Icing Characteristics of Water-Inertia-Separation Inlets for
Turbojet-Engine Ice Protection. NACA RM E50E03, 1950.

Wing Icing Protection

84. Hardy, J.K.: An Analysis of the Dissipation of Heat in Conditions of
N81-73130 Icing from a Section of the Wing of the C-46 Airplane.
NACA TR 831, 1945.

85. Bergrun, N.R., and Neel, C.B.: The Calculation of the Heat Required
N81-73131 for Wing Thermal Ice Prevention in Specified Icing Conditions.
NACA TN 1472, 1947.

86. Gray, V.H., Bowden, D.T., and von Glahn, U.: Preliminary Results of
N81-73132 Cyclical De-Icing of a Gas-Heated Airfoil. NACA RM E51J29, 1952.

87. Lewis, J.P., and Bowden, D.T.: Preliminary Investigation of Cyclic
N81-73133 De-Icing of an Airfoil Using an External Electric Heater.
NACA RM E51J30, 1952.

88. Gelder, T.F., and Lewis, J.P.: Comparison of Heat Transfer from
N81-73134 Airfoil in Natural and Simulated Icing Conditions.
NACA TN 2480, 1951.

89. Callaghan, E.E., and Serafini, J.S.: A Method for Rapid Determination
N81-73135 of the Icing Limit of a Body in Terms of the Stream Conditions.
NACA TN 2914, 1953.

90. Callaghan, E.E., and Serafini, J.S.: Analytical Investigation of
N81-73005 Icing Limit for Diamond-Shaped Airfoil in Transonic and Supersonic
Flow. NACA TN 2861, 1953.

91. Ruggeri, R.S.: De-Icing and Runback Characteristics of Three Cyclic
N81-73006 Electric, External De-Icing Boots Employing Chordwise Shedding.
NACA RM E53C26, 1953.

92. Gray, V.H., and Bowden, D.T.: Comparison of Several Methods of
N81-73023 Cyclic De-Icing of a Gas-Heated Airfoil. NACA RM E53C27, 1953.

93. Neel, C.B., Jr.: The Design of Air-Heated Thermal Ice-Prevention
N81-73024 Systems. (Presented at the Airplane Icing Information Course at the
University of Michigan, March 30 - April 3, 1953). NACA TN-3130, 1954.

94. Bowden, D.T.: Investigation of Porous Gas-Heated Leading-Edge Section
N81-73025 for Icing Protection of a Delta Wing. NACA RM E54I03, 1955.

95. Gray, V.H., and von Glahn, U.H.: Heat Requirements for Ice Protection
N81-73136 of a Cyclically Gas-Heated, 36° Swept Airfoil with Partial-Span
Leading-Edge Slat. NACA RM E56B23, 1956.

96. Gowan, W.H. and Mulholland, D.R.: Effectiveness of Thermal-Pneumatic
N81-73026 Airfoil-Ice-Protection System. NACA RM E50K10a, 1951.

Performance Penalties

97. von Glahn, U.H., and Gray, V.H.: Effect of Ice Formations on Section
N81-73007 Drag of Swept NACA 63A-009 Airfoil with Partial-Span Leading-Edge
Slat for Various Modes of Thermal Ice Protection.
NACA RM E53J30, 1954.

98. Gray, V.H., and von Glahn, U.H.: Effect of Ice and Frost Formations
N81-73008 on Drag of NACA 65_1-212 Airfoil for Various Modes of Thermal Ice
Protection. NACA TN 2962, 1953.

99. Preston, G.M., and Blackman, C.C.: Effects of Ice Formations on
N81-73027 Airplane Performance in Level Cruising Flight. NACA TN 1598, 1948.

100. Gelder, T.F., Lewis, J.P., and Koutz, S.L.: Icing Protection for
N81-73028 a Turbojet Transport Airplane: Heating Requirements, Methods of
Protection, and Performance Penalties. NACA TN 2866, 1953.

101. Bowden, D.T.: Effect of Pneumatic De-Icers and Ice Formations on
N81-73009 Aerodynamic Chrracteristics of an Airfoil. NACA TN 3564, 1956.

102. Gray, V.H.: Correlations Among Ice Measurements, Impingement Rates,
N81-73010 Icing Conditions and Drag of a 65A004 Airfoil. NACA TN 4151, 1958.

103. Gray, V.H. and von Glahn, U.H.: Aerodynamic Effects Caused by Icing
N81-73011 of an Unswept NACA 65A-004 Airfoil. NACA TN 4155, 1958.

104. Gray, V.H.: Prediction of Aerodynamic Penalties Caused by Ice
N81-73012 Formations on Various Airfoils. NASA TN D-2166, 1964.

Windshield Icing Protection

105. Holdaway, G.H., Steinmetz, C.P., and Jones, A.R.: A Method for
N81-73137 Calculating the Heat Required for Windshield Thermal Ice Prevention
Based on Extensive Flight Test in Natural Icing Conditions.
NACA TN 1434, 1947.

106. Ruggeri, R.S.: Preliminary Data on Rain Deflection from Aircraft
N81-73138 Windshields by Means of High-Velocity Jet-Air Blast.
NACA RM E55E17a, 1955.

Cooling Fan Icing Protection

107. Lewis, J.P.: Wind-Tunnel Investigation of Icing of an Engine
N81-73055 Cooling-Fan Installation. NACA TN 1246, 1947.

Radome Icing Protection

108. Lewis, J.P.: An Analytical Study of Heat Requirements for Icing
N81-73139 Protection of Radomes. NACA RM E53A22, 1953.

109. Lewis, J.P., and Blade, R.J.: Experimental Investigation of Radome
N81-73029 Icing and Icing Protection. NACA RM E52J31, 1953.

Antenna Icing

110. Kepple, W.L.: Determination of Aircraft Antenna Loads Produced by
N81-73166 Natural Icing Conditions. NACA RM E7H26a, 1948.

111. Gowan, W.H., Jr.: Vibration and Icing Investigation of CAA Type V-109
N81-73167 Very-High-Frequency Aircraft Antenna. NACA RM SE9D20, 1949.

Inlet and Vent Icing Protection

112. Ruggeri, R.S., von Glahn, U., and Rollin, V.G.: Investigation of
N81-73013 Aerodynamic and Icing Characteristics of Recessed Fuel-Vent Configurations. NACA TN 1789, 1949.

Jet Penetration

113. Callaghan, E.E., and Ruggeri, R.S.: Investigation of the Penetration
N81-73140 of an Air Jet Directed Perpendicularly to an Airstream. NACA TN 1615, 1948.

114. Ruggeri, R.S., Callaghan, E.E., and Bowden, D.T.: Penetration of
N81-73141 Air Jets Issuing from Circular, Square, and Elliptical Orifices Directed Perpendicularly to an Airstream. NACA TN 2019, 1950.

115. Callaghan, E.E., and Bowden, D.T.: Investigation of Flow Coefficients
N81-73142 of Circular, Square, and Elliptical Orifices at High Pressure Ratios. NACA TN 1947, 1949.

116. Ruggeri, R.S.: General Correlation of Temperature Profiles Downstream
N81-73143 of a Heated Air Jet Directed at Various Angles to Airstream. NACA TN 2855, 1952.

117. Callaghan, E.E., and Ruggeri, R.S.: A General Correlation of
N81-73144 Temperature Profiles Downstream of a Heated Air Jet Directed Perpendicularly to an Airstream. NACA TN 2466, 1951.

Heat Transfer

118. Gray, V.H.: Improvements in Heat Transfer for Anti-Icing of
N81-73030 Gas-Heated Airfoils with Internal Fins and Partitions. NACA TN 2126, 1950.

119. Gray, V.H.: Simple Graphical Solution of Heat Transfer and Evaporation
N81-73145 from Surface Heated to Prevent Icing. NACA TN 2799, 1952.

120. Callaghan, E.E.: Analogy between Mass and Heat Transfer with Turbulent
N81-73146 Flow. NACA TN 3045, 1953.

121. Coles, W.D., and Ruggeri, R.S.: Experimental Investigation of
N81-73147 Sublimation of Ice at Subsonic and Supersonic Speeds and its Relation to Heat Transfer. NACA TN 3104, 1954.

122. Coles, W.D.: Experimental Determination of Thermal Conductivity of
N81-73066 Low-Density Ice. NACA TN 3143, 1954.

123. Coles, W.D.: Icing Limit and Wet-Surface Temperature Variation for
N81-73014 Two Airfoil Shapes under Simulated High-Speed Flight Conditions. NACA TN 3396, 1955.

124. von Glahn, U.: Preliminary Results of Heat Transfer from a
N81-73148 Stationary and Rotating Ellipsoidal Spinner. NACA RM E53F02, 1953.

<u>Miscellaneous</u>

125. Gray, V.H.: Correlation of Airfoil Ice Formations and Their
N81-73015 Aerodynamic Effects with Impingement and Flight Conditions. (Presented at the SAE National Aeronautics Meeting - Sept. 30 - Oct. 5, 1957), SAE Preprint No. 225. (N-56390)

126. von Glahn, U.H.: The Icing Problem: Current Status of NACA
N81-73016 Techniques and Research. (Paper presented at Ottawa AGARD Conference), June 10-17, 1955. AG 19/P9. (N-37766)

127. von Glahn, U.H.: Some Considerations of the Need for Icing
N81-73031 Protection of High-Speed, High-Altitude Airplanes. NACA Conference on Some Problems of Aircraft Operation, November 17-18, 1954. NASA TM X-54700, pp. 21.1-21.7. (N64-85274)

128. Lewis, W. and Perkins, P.J.: A Flight Evaluation and Analysis of
N81-73017 the Effect of Icing Conditions on the PG-2 Airship. NACA TN 4220, 1958.

129. Lewis, W.: Icing Conditions to be Expected in the Operation of
N81-73289 High-Speed, High-Altitude Airplanes. NACA Conference on Some Problems of Aircraft Operation, November 17-18, 1954. NASA TM X-54700, pp. 20.1-20.9. (N64-85274)

130. NACA Conference on Aircraft Ice Prevention. A compilation of the
N81-73018 Papers Presented by NACA Staff Members. June 26-27, 1947. (6505/NACA-1947/8)

131. Gray, V.H.: Heat Requirements for Ice Prevention on Gas-Heated
N81-73056 Propellers. (Presented at SAE Annual Meeting, January 9-13, 1950), SAE Preprint No. 424. (1201.11-203)

132. Bowden, D.T., Gensemer, A.E., and Speen, C.A.: Engineering Summary of Airframe Icing Technical Data. Federal Aviation Agency, FAA-ADS-4, 1964. AD-608865 (N65-10209)

SUMMARIES/ABSTRACTS OF DOCUMENTS

LISTED IN BIBLIOGRAPHY

Meteorology of Icing Clouds

1 NACA TN 2738
National Advisory Committee for Aeronautics.
A PROBABILITY ANALYSIS OF THE METEORO-LOGICAL FACTORS CONDUCTIVE TO AIRCRAFT ICING IN THE UNITED STATES. William Lewis and Norman R. Bergrun. June 1952. 93p. diagrs., 11 tabs. (NACA TN 2738)

Meteorological icing data obtained in flight in the United States are analyzed statistically and methods are developed for the determination of (1) the various simultaneous combinations of the three basic icing parameters (liquid-water content, drop diameter, and temperature) which would have equal probability of being exceeded in flight in any random icing encounter, and (2) the probability of exceeding any specified group of values of liquid-water content associated simultaneously with temperature and drop-diameter values lying within specified ranges.
method provides a convenient means of calculating the percentage of icing encounters in which the water collection rate exceeds the design rate.

2 NACA TN 2569
National Advisory Committee for Aeronautics.
A SUMMARY OF METEOROLOGICAL CONDITIONS ASSOCIATED WITH AIRCRAFT ICING AND A PROPOSED METHOD OF SELECTING DESIGN CRITERIONS FOR ICE-PROTECTION EQUIPMENT Paul T. Hacker and Robert G. Dorsch. November 1951. 35p. diagrs. (NACA TN 2569)

Data on the meteorological parameters pertinent to the aircraft icing problem are so summarized as to give the frequency of occurrence of observed icing situations according to two of the parameters. The summarized data indicate that statistical relations exist between some of the parameters. A method, based upon the collection efficiency of an airfoil and the frequency of occurrence of icing situations with various liquid-water contents and mean-effective droplet sizes, is proposed for the selection of design criterions for ice-protection equipment.

3 NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE NO. 1855

RECOMMENDED VALUES OF METEOROLOGICAL FACTORS TO BE CONSIDERED IN THE DESIGN OF AIRCRAFT ICE-PREVENTION EQUIPMENT

By Alun R. Jones and William Lewis

SUMMARY

Meteorological conditions conducive to aircraft icing are arranged in four classifications: three are associated with cloud structure and the fourth with freezing rain. The range of possible meteorological factors for each classification is discussed and specific values recommended for consideration in the design of ice-prevention equipment for aircraft are selected and tabulated. The values selected are based upon a study of the available observational data and theoretical considerations where observations are lacking. Recommendations for future research in the field are presented.

4 Investigation of Meteorological Conditions Associated with Aircraft Icing in Layer-Type Clouds for 1947-48 Winter.

By Dwight B. Kline

NACA TN No. 1793
January 1949

Abstract

Measurements of liquid-water content, drop size, and temperature during icing conditions encountered in flight are shown to be consistent with previously measured conditions and with proposed maximum icing conditions in supercooled layer-type clouds. Cumulative-frequency graphs of meteorological parameters are presented indicating the frequency with which various icing conditions have been encountered in the Great Lakes area and surrounding states during two winters of flight observations.

5 Meteorological Analysis of Icing Conditions Encountered in Low-Altitude Stratiform Clouds.

By Dwight B. Kline and Joseph A. Walker

NACA TN 2306
March 1951

Abstract

Liquid-water content, droplet size, and temperature data measured in predominantly stratiform clouds during the 1948-49 and 1949-50 winters are presented. The horizontal and vertical extent of icing conditions and the relation of the existence of supercooled clouds to cyclone areas and precipitation regions are indicated. Liquid-water content measurements during 12 flights are shown in relation to theoretical amounts calculated from radiosonde data and cloud depth observations.

6 NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE NO. 1391

ICING PROPERTIES OF NONCYCLONIC WINTER STRATUS CLOUDS

By William Lewis, U.S. Weather Bureau

SUMMARY

Measurements of the vertical distribution of liquid water concentration and drop size have been made in winter stratus clouds in the absence of significant cyclonic or frontal activity. The observations indicate that the clouds are formed by turbulent mixing of the lower layers of the atmosphere, resulting in a region of constant specific humidity and adiabatic lapse rates. Calculations based on these characteristics were used to construct a graph which gives the liquid water concentration in terms of the temperature at the cloud base and the height above the base. In clouds from which no snow was falling, the measured values were in good agreement with those given by the graph. Snowfall was found to deplete the liquid water content especially in the lower part of the cloud layer, causing dissipation of the cloud from the base upwards.

7 Observations of Icing Conditions Encountered in Flight During 1948.

By William Lewis and Walter H. Hoecker, Jr.

NACA TN 1904

June 1949

Abstract

Meteorological data from 40 flights in icing conditions are presented. The report also includes a discussion of the relation between the horizontal extent of icing conditions and the average liquid-water content observed therein, the reliability of flight measurements of drop-size distribution, and an apparent geographical influence upon the size of cloud drops.

8 A Further Investigation of the Meteorological Conditions Conducive to Aircraft Icing

By William Lewis, Dwight B. Kline, and Charles P. Steinmetz

NACA TN No. 1424
October, 1947

Abstract

Data from flight observations in icing conditions on liquid water content, temperature, and mean-effective drop diameter are shown to be consistent with previously proposed values. Data on drop-size distribution with the rotating-cylinder method, although consistent with previous data, were inconsistent with data derived from stationary cylinder investigations. The relation between temperature and maximum water content in layer clouds is discussed and estimates are given for the highest values of water to be expected in layer clouds at various temperatures.

9 NACA RM E52J06
National Advisory Comm...ee for Aeronautics.
PRELIMINARY SURVEY OF ICING CONDITIONS MEASURED DURING ROUTINE TRANSCONTINENTAL AIRLINE OPERATION. Porter J. Perkins. December 1952. 27p. diagrs., photos., 3 tabs. (NACA RM E52J06)
Icing data collected on routine operations by four DC-4-type transport aircraft equipped with NACA pressure-type icing-rate meters and flying over a transcontinental route from January through May 1951 are presented. The four aircraft were in icing conditions approximately 1-1/2 percent of the total flying time. Nearly one-half of the icing conditions were encountered over the Great Lakes area. Average liquid-water-content measurements did not exceed 1.0 gram per cubic meter and 80 percent of the measurements did not exceed 0.4 gram per cubic meter. The data are considered only preliminary and the program is continuing to provide additional data from world-wide air routes.

10 NACA RM E55F28a
National Advisory Committee for Aeronautics.
STATISTICAL SURVEY OF ICING DATA MEASURED ON SCHEDULED AIRLINE FLIGHTS OVER THE UNITED STATES AND CANADA FROM NOVEMBER 1951 TO JUNE 1952. Porter J. Perkins. September 1955. 44p. diagrs., photos., 2 tabs. (NACA RM E55F28a)

A statistical survey and a preliminary analysis are made in an interim report of over 600 icing encounters obtained from a continuing program sponsored by the NACA with the cooperation of the airlines. Pressure-type icing-rate meters were installed on 11 airline aircraft of various types. Icing conditions measured during scheduled operations gave relative frequencies of liquid-water content, icing rate, total ice accumulations, cloud temperatures, as well as horizontal and vertical extent of icing clouds. Liquid-water contents were higher than data from earlier research flights in layer-type clouds but slightly lower than previous data from cumulus clouds.

11 NACA TN 4314
National Advisory Committee for Aeronautics.
ICING FREQUENCIES EXPERIENCED DURING CLIMB AND DESCENT BY FIGHTER-INTERCEPTOR AIRCRAFT. Porter J. Perkins. July 1958. 30p. diagrs., tabs. (NACA TN 4314)

Relative frequencies of occurrence and severity of icing cloud layers encountered up to an altitude of 30,000 feet are presented. Jet fighters on routine operations of the Air Defense Command (USAF) near Duluth, Minnesota, and Seattle, Washington, were equipped with icing meters for 1 year. Icing occurred on approximately 5 percent of the flights, with ice-accretion thickness averaging less than 1/32 inch on a small sensing probe. Probabilities of icing severity (including average liquid-water content and maximum ice accretion) were calculated using earlier data measured in icing clouds.

12 NACA RM E51D18
National Advisory Committee for Aeronautics.
ANALYSIS OF METEOROLOGICAL DATA OBTAINED DURING FLIGHT IN A SUPERCOOLED STRATIFORM CLOUD OF HIGH LIQUID-WATER CONTENT. Porter J. Perkins and Dwight B. Kline. July 1951. 18p. diagrs., photos. (NACA RM E51D18)

Flight icing-rate data obtained in a dense and abnormally deep supercooled stratiform cloud system in the vicinity of Lake Erie indicated the existence of liquid-water contents generally exceeding values in amount and extent previously reported over the midwestern sections of the United States. Additional information obtained during descent through a part of the cloud system indicated liquid-water contents that significantly exceeded theoretical values, especially near the middle of the cloud layer.

13 NACA TN 3984
National Advisory Committee for Aeronautics.
STATISTICAL STUDY OF AIRCRAFT ICING PROBABILITIES AT THE 700- AND 500-MILLIBAR LEVELS OVER OCEAN AREAS IN THE NORTHERN HEMISPHERE. Porter J. Perkins, William Lewis, and Donald R. Mulholland. May 1957. 31p. diagrs., tabs. (NACA TN 3984)

A statistical study is made of icing observations reported from weather reconnaissance aircraft flown by Air Weather Service (USAF). Wide areas of the Pacific, Atlantic, and Arctic Oceans were surveyed at fixed flight levels of 500 mb (18,000 ft) and 700 mb (10,000 ft). Icing statistics presented include the relative frequencies of the occurrence of icing, the estimated probability of flight in icing, and the relation of these probabilities to the frequencies of flight in clouds and cloud temperatures. Icing probabilities varied widely throughout the year from near zero in cold Arctic areas in winter up to 7 percent in areas where greater cloudiness and warmer temperatures prevail.

14 NASA MEMO 1-19-59E
National Aeronautics and Space Administration.
SUMMARY OF STATISTICAL ICING CLOUD DATA MEASURED OVER UNITED STATES AND NORTH ATLANTIC, PACIFIC, AND ARCTIC OCEANS DURING ROUTINE AIRCRAFT OPERATIONS. Porter J. Perkins. January 1959. 89p. diagrs., photos., tabs.
(NASA MEMORANDUM 1-19-59E)

Data and statistics needed in aircraft design and operation are presented from icing-cloud measurements and observations obtained during an extensive program conducted in cooperation with several airlines and the United States Air Force. Icing meters installed on 72 service aircraft supplied information for determining the liquid-water content and distance traveled in 1300 icing-cloud encounters. Other icing-cloud parameters measured were the temperature and depth of icing-cloud layers and a reference total ice accretion for each encounter. All results are tabulated and the measured parameters are summarized as frequency distributions.

15 **Statistical Explanation of Spontaneous Freezing of Water Droplets.**

By Joseph Levine

NACA TN 2234

December 1950

Abstract

A statistical theory based on the presence of small crystallization nuclei suspended in water is developed to explain experimental results showing that on the average small droplets can be supercooled to lower temperatures than large ones. Small nuclei of crystallization are assumed responsible for causing supercooled water to freeze spontaneously.

The average behavior of supercooled droplets is reproduced on the basis of probability theory with an assumed distribution of crystallization nuclei with respect to the temperatures at which the nuclei cause freezing. The most probable distribution curves of spontaneous freezing temperatures for water droplets of various sizes within the size range found in clouds are obtained.

16 Photomicrographic Investigation of Spontaneous Freezing Temperatures of Supercooled Water Droplets

By Robert G. Dorsch and Paul T. Hacker

NACA TN 2142

July 1950

Abstract

Data obtained by a photomicrographic technique on the spontaneous freezing temperatures of supercooled water droplets of the size ordinarily found in the atmosphere are presented.

The spontaneous freezing temperature was found to depend on droplet size.

Frequency distribution curves of the spontaneous freezing temperatures observed for a given droplet size were obtained.

17 NACA TN 2510
National Advisory Committee for Aeronautics.
EXPERIMENTAL VALUES OF THE SURFACE TENSION OF SUPERCOOLED WATER. Paul T. Hacker. October 1951. 20p. diagrs., photos., tab. (NACA TN 2510)

The surface tension of water has been determined experimentally for the temperature range, 0° to -22.2° C. The weak inflection point in the surface-tension - temperature relation, as indicated by the International Critical Table values for temperatures down to -8° C, was substantiated by the measurements in the temperature range, 0° to -22.2° C. The surface tension increases at approximately a linear rate from a value of 76.96 ± 0.06 dynes per centimeter at -8° C to 79.67 ± 0.06 dynes per centimeter at -22.2° C.

18 NACA TN 2532
National Advisory Committee for Aeronautics.
X-RAY DIFFRACTION STUDY OF THE INTERNAL STRUCTURE OF SUPERCOOLED WATER. Robert G. Dorsch and Bemrose Boyd. October 1951. 14p. diagrs., photo. (NACA TN 2532)

X-ray diffraction data for water in the temperature range 21° to -16° C are presented. The minimum between the two main diffraction peaks deepened continuously, as the temperature was lowered. It is concluded that supercooled water apparently becomes progressively more ice-like in structure as the temperature is lowered.

19 NACA RM E51L17
National Advisory Committee for Aeronautics.
A PHOTOGRAPHIC STUDY OF FREEZING OF WATER DROPLETS FALLING FREELY IN AIR.
Robert G. Dorsch and Joseph Levine. February 1952. 29p. diagrs., photos., 2 tabs. (NACA RM E51L17)

The freezing of free-falling water droplets in air was investigated by a photographic technique. Information on the following was obtained: (1) droplet shape after freezing, (2) the occurrence of collisions of partly frozen or frozen and liquid droplets, and (3) the freezing temperatures of individual free-falling droplets.

20 NACA TN 3024
National Advisory Committee for Aeronautics.
MAXIMUM EVAPORATION RATES OF WATER DROPLETS APPROACHING OBSTACLES IN THE ATMOSPHERE UNDER ICING CONDITIONS.
Herman H. Lowell. October 1953. 56p. diagrs., 3 tabs. (NACA TN 3024)

Maximum possible evaporation rates of water droplets approaching obstacles in the atmosphere along stagnation lines or moving within intake ducts of airplanes under icing conditions were calculated for a wide variety of ambient conditions, flight Mach numbers, degrees of stagnation of the incident relative air stream, and droplet diameters. Droplet diameter, body size, and flight Mach number effects were found to predominate, whereas wide variation in ambient conditions had little effect on evaporative losses. It was concluded that little or no evaporative loss occurs from droplets approaching small obstacles such as liquid-water-content measurement cylinders, whereas losses may be as high as several percent in the case of larger obstacles such as wings, or 50 percent in the case of ducts at high ram pressure. Losses in ducts in general, however, will usually be about 10 to 20 percent.

21

Kinetic Temperature of Wet Surfaces

A Method of Calculating the Amount of Alcohol Required to Prevent Ice, and the Derivation of the Psychrometric Equation

By

J. K. HARDY*

of the Royal Aircraft Establishment

Reports and Memoranda No. 2830

September, 1945

Summary. – A method is given for calculating the temperature of a surface wetted either by a pure liquid, such as water, or by a mixture, such as alcohol and water. The method is applied to the problem of protecting, by alcohol, propellers and the induction system of the engine against ice. The minimum quantity of alcohol required is calculated for a number of arbitrarily chosen conditions. The effect of evaporation of alcohol is shown by repeating the calculations for a non-volatile fluid. The method can be applied to other problems in evaporation, for instance, to the evaporation of fuel in the induction system of the engine. The psychrometric equation, used in wet-bulb hygrometry, is deduced in its general form. The effect of kinetic heating is included in this equation.

Meteorological Instruments

22

NACA TN 2615
National Advisory Committee for Aeronautics.
THE CALCULATED AND MEASURED PERFORMANCE CHARACTERISTICS OF A HEATED-WIRE LIQUID-WATER-CONTENT METER FOR MEASURING ICING SEVERITY. Carr B. Neel, Jr. and Charles P. Steinmetz. January 1952. 59p. diagrs., photos., 6 tabs. (NACA TN 2615)

Initial development has been made of an instrument which could be used to obtain statistical flight data on the liquid-water content of icing clouds and to provide a direct indication of icing severity. The sensing element of the instrument consists of a wire of known temperature-resistance characteristics which is heated by passing electrical current through it. The wire is mounted in the air stream and the degree of cooling resulting from evaporation of impinging water droplets is a measure of the liquid-water content of the cloud. Comparisons are made of the liquid-water content as measured with heated wires and absorbent cylinders in an artificially produced cloud. Performance characteristics of a heated-wire instrument are presented.

23 NACA RM E53D23
National Advisory Committee for Aeronautics.
PROCEDURE FOR MEASURING LIQUID-WATER CONTENT AND DROPLET SIZES IN SUPERCOOLED CLOUDS BY ROTATING MULTICYLINDER METHOD. William Lewis, Porter J. Perkins and Rinaldo J. Brun. Appendix C: ALTERNATE METHOD OF REDUCING ROTATING MULTICYLINDER DATA. Paul T. Hacker. June 1953. 48p. diagrs., photos., 4 tabs. (NACA RM E53D23)

The rotating multicylinder method for in-flight determination of liquid-water content, droplet size, and droplet-size distribution in icing clouds is described. The theory of operation, the apparatus required, the technique of obtaining data in flight, and detailed methods of calculating the results, including necessary charts and tables, are presented.

24 NACA RM E50K01a
National Advisory Committee for Aeronautics.
FLIGHT CAMERA FOR PHOTOGRAPHING CLOUD DROPLETS IN NATURAL SUSPENSION IN THE ATMOSPHERE. Stuart McCullough and Porter J. Perkins. June 1951. 23p. diagrs., photos. (NACA RM E50K01a)

A camera designed for use in flight has been developed by the NACA Lewis laboratory to photograph cloud droplets in their natural suspension in the atmosphere. A magnification of 32 times is employed to distinguish for measurement purposes all sizes of droplets greater than 5 microns in diameter. Photographs can be taken at flight speeds up to 150 miles per hour at 5-second intervals. A field area of 0.025 square inch is photographed on 7-inch-width roll film accommodating 40 exposures on an 18-foot length. Flight tests conducted in cumulus clouds have shown that approximate droplet-size distribution studies can be obtained and that studies of the microstructure and physics of clouds can be made with the camera.

25 Flight Instrument for Measurement of Liquid-Water Content in Clouds at Temperatures above and below Freezing.

By Porter J. Perkins

NACA RM E50J12a

March 1951

Abstract

An instrument consisting of a small cylindrical element operated at high surface temperatures was developed to provide a simple and rapid means of determining the liquid-water content of clouds at temperatures above and below freezing.

The instrument was sensitive to a wide range of liquid-water content and was calibrated against rotating multicylinder measurements at an air temperature of 20° F, an air velocity of 175 miles per hour, and a surface temperature in clear air of 475° F.

26 NACA RM E51E16
National Advisory Committee for Aeronautics.
A SIMPLIFIED INSTRUMENT FOR RECORDING AND INDICATING FREQUENCY AND INTENSITY OF ICING CONDITIONS ENCOUNTERED IN FLIGHT.
Porter J. Perkins, Stuart McCullough and Ralph D. Lewis. July 1951. 26p. diagrs., photos. (NACA RM E51E16)

An instrument for recording and indicating the frequency and intensity of aircraft icing conditions encountered in flight has been developed by the NACA Lewis Laboratory to obtain statistical icing data over world-wide air routes during routine airline operations. The operation of the instrument is based on the creation of a differential pressure between an ice-free total-pressure system and a total-pressure system in which small total-pressure holes vented to static pressure are allowed to plug with ice accretion. The simplicity of this operating principle permits automatic operation, and provides relative freedom from maintenance and operating problems. The complete unit weighing only 18 pounds records icing rate, airspeed, and altitude on photographic film and provides visual indications of icing intensity to the pilot.

27 NACA TN 2458

National Advisory Committee for Aeronautics.
AN INSTRUMENT EMPLOYING A CORONAL DISCHARGE FOR THE DETERMINATION OF DROPLET-SIZE DISTRIBUTION IN CLOUDS.
Rinaldo J. Brun, Joseph Levine, and Kenneth S. Kleinknecht. September 1951. 53p. diagrs., photos., 4 tabs. (NACA TN 2458)

A flight instrument that uses electric means for obtaining a measure of the droplet-size distribution in above-freezing clouds has been devised and given preliminary evaluation in flight. An electric charge is placed on the droplets and they are separated aerodynamically according to their mass. The desirable features of an instrument based on the method described are: (1) the instrument can be used in clouds with temperatures above freezing, (2) the size and the shape of the cylinders do not change during the exposure time, (3) the error caused by bounce-off is low, (4) the readings are instantaneous and continuous, and (5) the fast instrument response permits the study of variations in cloud structure.

28 NACA RM E51G05

National Advisory Committee for Aeronautics.
ADAPTATION OF A CASCADE IMPACTOR TO FLIGHT MEASUREMENT OF DROPLET SIZE IN CLOUDS. Joseph Levine and Kenneth S. Kleinknecht. September 1951. 28p. diagrs., photos. (NACA RM E51G05)

A cascade impactor, an instrument for obtaining the size distribution of droplets borne in a low-velocity air stream, has been adapted for flight cloud droplet studies. Data from two flights are presented.

29 NACA TN 2708
National Advisory Committee for Aeronautics.
COMPARISON OF THREE MULTICYLINDER ICING METERS AND CRITIQUE OF MULTICYLINDER METHOD. Wallace E. Howell, Mount Washington Observatory. June 1952. 40p. diagrs., photos., 6 tabs. (NACA TN 2708)

Three multicylinder icing meters, fundamentally similar but differing from each other in important deisgn details, were compared in use at the Mount Washington Observatory. Comparison of relative effectiveness of the instruments, evaluation of observational errors, determination of the effects of detailed design differences, and recommendations for further improvements of design are presented. An evaluation of the multicylinder method, concerned with the validity of the theoretical basis and the degree to which the instruments and the technique of their use permit accurate determinations of the physical measurements involved, is also included.

30 A Review of Instruments Developed for the Measurement of the Meteorological Factors Conducive to Aircraft Icing.

By Alun R. Jones and William Lewis

NACA RM No. A9C09

April 1949

Abstract

The status of instruments suitable for the measurement of the meteorological factors conducive to aircraft icing is reviewed. The factors to be evaluated are listed, and tentative values for the desired and acceptable accuracy of measurement for each factor are suggested.

Nine instruments which appear to be the most promising for the procurement of the meteorological data are discussed with respect to the quantities they measure, principle of operation, range and accuracy, duration of a single reading, and advantages and disadvantages associated with their use. Recommendations are presented for the continued research and development of icing meteorological instruments.

31 NACA RM A54I23
National Advisory Committee for Aeronautics.
A HEATED-WIRE LIQUID-WATER-CONTENT INSTRUMENT AND RESULTS OF INITIAL FLIGHT TESTS IN ICING CONDITIONS. Carr B. Neel. January 1955. 33p. diagrs., photos., tab. (NACA RM A54I23)

A flight model of the heated-wire instrument was tested in natural icing conditions, and was shown to provide reliable measurements of liquid-water content. The rapid response of the instrument enabled detailed study of cloud structure. Cloud-duct tests showed measurements could be made up to 700 mph. Results of the flight measurements substantiated the high values of water content previously predicted. The highest value measured was 3.7 grams per cubic meter.

32 NACA TN 3592
National Advisory Committee for Aeronautics.
AN OIL-STREAM PHOTOMICROGRAPHIC AEROSCOPE FOR OBTAINING CLOUD LIQUID-WATER CONTENT AND DROPLET SIZE DISTRIBUTIONS IN FLIGHT. Paul T. Hacker. January 1956. 36p. diagrs., photos., tabs. (NACA TN 3592)

An airborne cloud aeroscope by which droplet size, size distribution, and liquid-water content of icing and nonicing clouds can be determined has been developed and tested in flight and in wind tunnels with water sprays. The cloud droplets are continuously captured in a stream of oil, which is then photographed. In most cases, droplet size distribution can be obtained from a single photograph. With the droplet size distribution known, the liquid-water content of the cloud can be calculated from the geometry of the aeroscope, the airspeed, and the oil flow rate. The aeroscope is described in detail, and some droplet size distributions and liquid-water contents obtained during tests are presented.

33 NACA TN 2476
National Advisory Committee for Aeronautics.
AN EMPIRICAL METHOD PERMITTING RAPID DETERMINATION OF THE AREA, RATE, AND DISTRIBUTION OF WATER-DROP IMPINGEMENT ON AN AIRFOIL OF ARBITRARY SECTION AT SUBSONIC SPEEDS: Norman R. Bergrun. September 1951. 151p. diagrs., 11 tabs. (NACA TN 2476)

A method is developed which permits the determination of area, rate, and distribution of water-drop impingement on airfoils of arbitrary section at subsonic speeds. The method, which is based on the results of extensive water-drop-trajectory calculations for five airfoil cases, requires only a few simple numerical computations once the velocity distribution over the airfoil has been determined.

34 NACA

TECHNICAL NOTE No. 1397

A METHOD FOR NUMERICALLY CALCULATING THE AREA AND DISTRIBUTION OF WATER IMPINGEMENT ON THE LEADING EDGE OF AN AIRFOIL IN A CLOUD

Norman R. Bergrun

SUMMARY

A method is presented for determining, by step-by-step integration, the trajectories of water drops around any body in two-dimensional flow for which the streamline velocity components are known or can be computed. The method is general and considers the deviation of the water drops from Stokes' law because of speed and drop size.

The equations are presented in general form and then, to illustrate the procedure, water-drop trajectories are calculated about a 12-percent-thick symmetrical Joukowski profile chosen to simulate an NACA 0012 section.

The method provides a means for the relatively rapid calculation of the trajectory of a single drop without the utilization of a differential analyzer.

In addition, consideration is given to the maximum possible rate of water-drop impingement on a body.

35 NACA RM E52B12
National Advisory Committee for Aero `utics.
IMPINGEMENT OF WATER DROPLETS ON AN NACA 65_1-212 AIRFOIL AT AN ANGLE OF ATTACK OF 4°. Rinaldo J. Brun, John S. Serafini and George J. Moshos. September 1952. 47p. diagrs., tab. (NACA RM E52B12)

The trajectories of droplets in the air flowing past an NACA 65_1-212 airfoil at an angle of attack of 4° were determined. The collection efficiency, the area of droplet impingement, and the rate of droplet impingement were calculated from the trajectories. The results are applicable under the following conditions: chord lengths from 2 to 20 feet, altitudes from 1000 to 35,000 feet, airplane speeds from 150 miles per hour to the critical flight Mach number, and droplet diameters from 5 to 100 microns.

36 NACA TN 2999
National Advisory Committee for Aeronautics.
IMPINGEMENT OF DROPLETS IN 90° ELBOWS WITH POTENTIAL FLOW. Paul T. Hacker, Rinaldo J. Brun and Bemrose Boyd. September 1953. 58p. diagrs., 2 tabs. (NACA TN 2999)

Trajectories were determined for droplets in air flowing through 90° elbows especially designed for two-dimensional potential motion with low pressure losses. The elbows were established by selecting as walls of each elbow two streamlines of the flow field produced by a complex potential function that establishes a two-dimensional flow around a 90° bend. An unlimited number of elbows with slightly different shapes can be established by selecting different pairs of streamlines as walls. The elbows produced by the complex potential function selected are suitable for use in aircraft air-intake ducts. The droplet impingement data derived from the trajectories are presented along with equations in such a manner that the collection efficiency, the area, the rate, and the distribution of droplet impingement can be determined for any elbow defined by any pair of streamlines within a portion of the flow field established by the complex potential function. Coordinates for some typical streamlines of the flow field and velocity components for several points along these streamlines are presented in tabular form.

37 NACA Rept. 1159
National Advisory Committee for Aeronautics.
IMPINGEMENT OF WATER DROPLETS ON WEDGES AND DOUBLE-WEDGE AIRFOILS AT SUPERSONIC SPEEDS. John S. Serafini. 1954. ii, 24p. diagrs. (NACA Rept. 1159. Formerly TN 2971)

An analytical solution has been obtained for the equations of motion of water droplets impinging on a wedge in a two-dimensional supersonic flow field with a shock wave attached to the wedge. The closed-form solution yields analytical expressions for the equation of the droplet trajectory, the local rate of impingement and the impingement velocity at any point on the wedge surface, and the total rate of impingement. The analytical expressions are utilized to determine the impingement on the forward surfaces of diamond airfoils in supersonic flow fields with attached shock waves. The results presented include the following conditions: droplet diameters from 2 to 100 microns, pressure altitudes from sea level to 30,000 feet, free-stream static temperatures from 420° to 460° R, free-stream Mach numbers from 1.1 to 2.0, semiapex angles for the wedge from 1.14° to 7.97°, thickness-to-chord ratios for the diamond airfoil from 0.02 to 0.14, chord lengths from 1 to 20 feet, and angles of attack from zero to the inverse tangent of the airfoil thickness-to-chord ratio.

38 NACA TN 3047
National Advisory Committee for Aeronautics.
IMPINGEMENT OF WATER DROPLETS ON NACA 65A004 AIRFOIL AND EFFECT OF CHANGE IN AIRFOIL THICKNESS FROM 12 TO 4 PERCENT AT 4° ANGLE OF ATTACK. Rinaldo J. Brun, Helen M. Gallagher and Dorothea E. Vogt. November 1953. 45p. diagrs., tab. (NACA TN 3047)

The trajectories of droplets in the air flowing past an NACA 65A004 airfoil at an angle of attack of 4° were determined. The amount of water in droplet form impinging on the airfoil, the area of droplet impingement, and the rate of droplet impingement per unit area on the airfoil surface were calculated from the trajectories and presented to cover a large range of flight and atmospheric conditions. The effect of a change in airfoil thickness from 12 to 4 percent at 4° angle of attack is presented by comparing the impingement calculations for the NACA 65A004 airfoil with those for the NACA 65_1-208 and 65_1-212 airfoils. The rearward limit of impingement on the upper surface decreases as the airfoil thickness decreases. The rearward limit of impingement on the lower surface increases with a decrease in airfoil thickness. The total water intercepted decreases as the airfoil thickness is decreased.

39 NACA TN 2952
National Advisory Committee for Aeronautics.
IMPINGEMENT OF WATER DROPLETS ON NACA 65_1-208 AND 65_1-212 AIRFOILS AT 4^0 ANGLE OF ATTACK. Rinaldo J. Brun, Helen M. Gallagher and Dorothea E. Vogt. May 1953. 49p. diagrs. (NACA TN 2952)

The trajectories of droplets in the air flowing past an NACA 65_1-208 airfoil and an NACA 65_1-212 airfoil, both at an angle of attack of 4^0, were computed with a mechanical analog. The amount of water in droplet form impinging on the airfoils, the area of droplet impingement, and the rate of droplet impingement per unit area on the airfoil surface affected were calculated from the trajectories.

40 NACA TN 2904
National Advisory Committee for Aeronautics.
IMPINGEMENT OF WATER DROPLETS ON A CYLINDER IN AN INCOMPRESSIBLE FLOW FIELD AND EVALUATION OF ROTATING MULTICYLINDER METHOD FOR MEASUREMENT OF DROPLET-SIZE DISTRIBUTION, VOLUME-MEDIAN DROPLET SIZE, AND LIQUID-WATER CONTENT IN CLOUDS. Rinaldo J. Brun and Harry W. Mergler. March 1953. 71p. diagrs., photo., 4 tabs. (NACA TN 2904)

The trajectories of water droplets in an incompressible flow field around a cylinder were calculated with a mechanical analog. The collection efficiency, the area of droplet impingement on the cylinder, and the rate of droplet impingement were determined from the trajectories. An evaluation of the rotating multicylinder method for the measurement of droplet-size distribution, volume-median droplet size, and liquid-water content was made based on the results of the trajectory calculations.

41 NACA TN 2903
National Advisory Committee for Aeronautics.
IMPINGEMENT OF CLOUD DROPLETS ON AERODYNAMIC BODIES AS AFFECTED BY COMPRESSIBILITY OF AIR FLOW AROUND THE BODY.
Rinaldo J. Brun, John S. Serafini and Helen M. Gallagher. March 1953. 20p. diagrs. (NACA TN 2903)

The trajectories of water droplets in a compressible-air flow field around a cylinder were computed with a mechanical analog. The results of the calculations at the flight critical Mach number were compared with calculations of trajectories in an incompressible flow field. For a cylinder, the effect of compressibility of the air on the droplet trajectories was negligible up to the flight critical Mach number. The results obtained with the cylinder were extended to airfoils. This extension is possible because the incompressible flow fields of both cylinders and airfoils are similarly altered by compressibility.

42 Determination of Rate, Area, and Distribution of Impingement of Waterdrops on Various Airfoils from Trajectories Obtained on the Differential Analyzer.

By A. G. Guibert, E. Janssen, and W. M. Robbins

NACA RM No. 9A05

February 1949

Abstract

The trajectories of waterdrops in air flowing over airfoils are determined for three airfoil - angle-of-attack combinations using the differential analyzer to solve the differential equations of motion of the waterdrops. From these trajectories the rate of water impingement, the area of impingement, and the distribution of impingement are determined as functions of two dimensionless moduli.

Comparisons are made of the rate of water impingement on these airfoils and the rate of water impingement on cylinders.

43 NACA TN 2931
National Advisory Committee for Aeronautics.
A METHOD FOR DETERMINING CLOUD-DROPLET IMPINGEMENT ON SWEPT WINGS. Robert G. Dorsch and Rinaldo J. Brun. April 1953. 29p. diagrs. (NACA TN 2931)

The general effect of wing sweep on cloud-droplet trajectories about swept wings of high aspect ratio moving at subsonic speeds is discussed. A method of computing droplet trajectories about yawed cylinders and swept wings is presented, and illustrative droplet trajectories are computed. A method of extending two-dimensional calculations of droplet impingement on nonswept wings to swept wings is presented. It is shown that the extent of impingement of cloud droplets on an airfoil surface, the total rate of collection of water, and the local rate of impingement per unit area of airfoil surface can be found for a swept wing from two-dimensional data for a nonswept wing. The impingement on a swept wing is obtained from impingement data for a nonswept airfoil section which is the same as the section in the normal plane of the swept wing by calculating all dimensionless parameters with respect to flow conditions in the normal plane of the swept wing.

44 NACA TN 3147
National Advisory Committee for Aeronautics.
IMPINGEMENT OF WATER DROPLETS ON AN ELLIPSOID WITH FINENESS RATIO 10 IN AXISYMMETRIC FLOW. Rinaldo J. Brun and Robert G. Dorsch. May 1954. 37p. diagrs., tab. (NACA TN 3147)

The presence of radomes and instruments that are sensitive to water films or ice formations in the nose section of all-weather aircraft and missiles necessitates a knowledge of the droplet impingement characteristics of bodies of revolution. Because it is possible to approximate many of these bodies with an ellipsoid of revolution, droplet trajectories about an ellipsoid of revolution with a fineness ratio of 10 were computed for incompressible axisymmetric air flow. From the computed droplet trajectories, the following impingement characteristics of the ellipsoid surface were obtained and are presented in terms of dimensionless parameters: (1) total rate of water impingement, (2) extent of droplet impingement zone, and (3) local rate of water impingement. These impingement characteristics are compared briefly with those for an ellipsoid of revolution with a fineness ratio of 5 reported in NACA TN 3099.

45 NACA TN 3099
National Advisory Committee for Aeronautics.
IMPINGEMENT OF WATER DROPLETS ON AN ELLIPSOID WITH FINENESS RATIO 5 IN AXISYMMETRIC FLOW. Robert G. Dorsch, Rinaldo J. Brun and John L. Gregg. March 1954. 50p. diagrs., tab. (NACA TN 3099)

The presence of radomes and instruments that are sensitive to water films or ice formations in the nose section of all-weather aircraft and missiles necessitates a knowledge of the droplet impingement characteristics of bodies of revolution. Because it is possible to approximate many of these bodies with an ellipsoid of revolution, droplet trajectories about an ellipsoid of revolution with a fineness ratio of 5 were computed for incompressible axisymmetric air flow. From the computed droplet trajectories, the following impingement characteristics of the ellipsoid surface were obtained and are presented in terms of dimensionless parameters: (1) total rate of water impingement, (2) extent of droplet impingement zone, (3) distribution of impinging water, and (4) local rate of water impingement.

46 NACA TN 3153
National Advisory Committee for Aeronautics.
VARIATION OF LOCAL LIQUID-WATER CONCENTRATION ABOUT AN ELLIPSOID OF FINENESS RATIO 5 MOVING IN A DROPLET FIELD. Robert G. Dorsch and Rinaldo J. Brun. July 1954. 68p. diagrs., photos., 2 tabs. (NACA TN 3153)

Analyses of calculated water-droplet trajectories show that the concentration of liquid water at various points about an ellipsoid of revolution moving through a droplet field varies considerably. Curves of local concentration factor as a function of spatial position are presented in terms of dimensionless parameters.

47 NACA TN 3155
National Advisory Committee for Aeronautics.
IMPINGEMENT OF WATER DROPLETS ON NACA 65A004 AIRFOIL AT 8° ANGLE OF ATTACK.
Rinaldo J. Brun, Helen M. Gallagher and Dorothea E. Vogt. July 1954. 27p. diagrs. (NACA TN 3155)

The trajectories of droplets in the air flowing past an NACA 65A004 airfoil at an angle of attack of 8° were determined. The amount of water in droplet form impinging on the airfoil, the area of droplet impingement, and the rate of droplet impingement per unit area on the airfoil surface were calculated from the trajectories and presented to cover a large range of flight and atmospheric conditions. These impingement characteristics are compared briefly with those previously reported for the same airfoil at an angle of attack of 4°.

48 NACA TN 3410
National Advisory Committee for Aeronautics.
VARIATION OF LOCAL LIQUID-WATER CONCENTRATION ABOUT AN ELLIPSOID OF FINENESS RATIO 10 MOVING IN A DROPLET FIELD. Rinaldo J. Brun and Robert G. Dorsch. April 1955. 51p. diagrs., photo., tab. (NACA TN 3410)

Trajectories of water droplets about an ellipsoid of revolution with a fineness ratio of 10 (10 percent thick) in flight through a droplet field were computed with the aid of a differential analyzer. Analyses of these trajectories indicate that the local concentration of liquid water at various points about an ellipsoid varies considerably and under some conditions may be several times the free-stream concentration. Curves of the local concentration factor as a function of spatial position were obtained and are presented in terms of dimensionless parameters that describe flight and atmospheric conditions.

49 NACA TN 3338
National Advisory Committee for Aeronautics.
A DYE-TRACER TECHNIQUE FOR EXPERIMENTALLY OBTAINING IMPINGEMENT CHARACTERISTICS OF ARBITRARY BODIES AND A METHOD FOR DETERMINING DROPLET SIZE DISTRIBUTION.
Uwe H. von Glahn, Thomas F. Gelder and William H. Smyers, Jr. March 1955. 73p. diagrs., photos., tab. (NACA TN 3338)

A dye-tracer technique has been developed from which the droplet impingement characteristics of bodies can be determined by colorimetric analysis. The technique is applicable to various wind tunnels provided the humidity of the air stream can be maintained near saturation. A method is also presented whereby the droplet size distribution of the impinging cloud may be determined by relating the experimental impingement characteristics of a body to the theoretical trajectory results for the same body.

50 NACA TN 3587
National Advisory Committee for Aeronautics.
IMPINGEMENT OF WATER DROPLETS ON A SPHERE. Robert G. Dorsch, Paul G. Saper, and Charles F. Kadow November 1955. 29p. diagrs., tab. (NACA TN 3587)

Droplet trajectories about a sphere in ideal fluid flow were calculated. From the calculated droplet trajectories, the droplet-impingement characteristics of the sphere were determined. Impingement data and equations for determining the collection efficiency, the area, and the distribution of impingement are presented in terms of dimensionless parameters. The range of flight and atmospheric conditions covered in the calculations was extended considerably beyond the range covered by previously reported calculations for the sphere.

51 NACA TN 3658
National Advisory Committee for Aeronautics.
IMPINGEMENT OF WATER DROPLETS ON A RECTANGULAR HALF BODY IN A TWO-DIMENSIONAL INCOMPRESSIBLE FLOW FIELD. William Lewis and Rinaldo J. Brun. February 1956. 27p. diagrs., tabs. (NACA TN 3658)

Trajectories of water droplets moving in the ideal two-dimensional flow field ahead of a body of rectangular cross section and infinite extent in the downstream direction have been calculated by means of a differential analyzer. Data on collection efficiency and distribtuion of water impingement are presented.

52 NACA TN 3586
National Advisory Committee for Aeronautics.
IMPINGEMENT OF WATER DROPLETS ON NACA 65A004 AIRFOIL AT 0° ANGLE OF ATTACK. Rinaldo J. Brun and Dorothea E. Vogt. November 1955. 28p. diagrs. (NACA TN 3586)

The trajectories of droplets in the air flowing past an NACA 65A004 airfoil at an angle of attack of 0° were determined. The amount of water in droplet form impinging on the airfoil, the area of droplet impingement, and the rate of droplet impingement per unit area on the airfoil surface were calculated from the trajectories and presented to cover a large range of flight and atmospheric conditions. These impingement characteristics are compared briefly with those previously reported for the same airfoil at angles of attack of 4° and 8°.

53 **REPORT 1215**

IMPINGEMENT OF CLOUD DROPLETS ON A CYLINDER AND PROCEDURE FOR MEASURING LIQUID-WATER CONTENT AND DROPLET SIZES IN SUPERCOOLED CLOUDS BY ROTATING MULTICYLINDER METHOD[1]

By R. J. Brun, W. Lewis, P. J. Perkins, and J. S. Serafini

SUMMARY

Evaluation of the rotating multicylinder method for the measurement of droplet-size distribution, volume-median droplet size, and liquid-water content in clouds showed that small uncertainties in the basic data eliminate the distinction between different cloud droplet-size distributions and are a source of large errors in the determination of the droplet size. Calculations of the trajectories of cloud droplets in incompressible and compressible flow fields around a cylinder were performed on a mechanical analog constructed for the study of the trajectories of droplets around aerodynamic bodies. Many data points were carefully calculated in order to determine precisely the rate of droplet impingement on the surface of a right circular cylinder. From the computed droplet trajectories, the following impingement characteristics of the cylinder surface were obtained and are presented in terms of dimensionless parameters: (1) total rate of water impingement, (2) extent of droplet impingement zone, and (3) local distribution of impinging water on cylinder surface.

The rotating multicylinder method for in-flight determination of liquid-water content, droplet size, and droplet-size distribution in icing clouds is described. The theory of operation, the apparatus required, the technique of obtaining data in flight, and detailed methods of calculating the results, including necessary charts and tables, are presented. An evaluation of the multicylinder method includes the effect on final results of droplets that do not freeze completely on the cylinders after striking them, as well as probable errors in final results caused by the inherent insensitivity of the multicylinder method.

54 NACA Rept. 1317
National Advisory Committee for Aeronautics.
CLOUD-DROPLET INGESTION IN ENGINE INLETS WITH INLET VELOCITY RATIOS OF 1.0 AND 0.7.
Rinaldo J. Brun. 1957. ii, 35p. diagrs., tab.
(NACA Rept. 1317. Supersedes TN 3593)

The paths of cloud droplets into two engine inlets are calculated. The amount of water in droplet form ingested by the inlets and the amount and distribution of water impinging on the inlet walls are obtained from these droplet-trajectory calculations. In both types of inlet a prolate ellipsoid of revolution (10-percent thick) represents either part or all of the forebody at the center of an annular inlet to an engine. The configurations can also represent a fuselage of an airplane with side ram-scoop inlets. The principal difference between the two inlets studied is that the inlet air velocity of one is 0.7 that of the other.

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55 NACA TN 4268
National Advisory Committee for Aeronautics.
DROPLET IMPINGEMENT AND INGESTION BY SUPERSONIC NOSE INLET IN SUBSONIC TUNNEL CONDITIONS. Thomas F. Gelder. May 1958. 56p. diagrs., photos. (NACA TN 4268)

The amount of water in cloud droplet form ingested by a full-scale supersonic nose inlet with conical center body was measured. Local and total water impingement rates on the cowl and center-body surfaces were also obtained. All measurements were made with a dye-tracer technique. Inlet angles of attack of 0° and 4.2°, droplet diameters from 11 to 20 microns, and ratios of inlet to free-stream velocity from 0.4 to 1.8 were studied. Measurements were confined to a free-stream Mach number of 0.237 and are extendable to other subsonic speeds by dimensionless impingement parameters.

56 NACA TN 3839
National Advisory Committee for Aeronautics.
EXPERIMENTAL DROPLET IMPINGEMENT ON SEVERAL TWO-DIMENSIONAL AIRFOILS WITH THICKNESS RATIOS OF 6 TO 16 PERCENT. Thomas F. Gelder, William H. Smyers, Jr., and Uwe von Glahn. December 1956. 77p. diagrs., photos., tabs. (NACA TN 3839)

The rate and area of cloud droplet impingement on several two-dimensional swept and unswept airfoils were obtained experimentally in the NACA Lewis icing tunnel with a dye-tracer technique. Airfoil thickness ratios of 6 to 16 percent, angles of attack from 0° to 12°, and chord sizes from 13 to 96 inches were included in the study. The results are presented in the form of dimensionless impingement parameters in order to cover a wide range of flight and atmospheric conditions.

57 NACA TN 3770
National Advisory Committee for Aeronautics.
IMPINGEMENT OF DROPLETS IN 60° ELBOWS WITH POTENTIAL FLOW. Paul T. Hacker, Paul G. Saper, and Charles F. Kadow. October 1956. 54p. diagrs., tabs. (NACA TN 3770)

Theoretical trajectories were determined for droplets in air flowing through 60° elbows. The elbows were established by selecting as walls of each elbow two streamlines of a two-dimensional flow field produced by a complex potential function. These elbows are suitable for use in aircraft air-inlet ducts. Droplet impingement data are presented in terms of dimensionless parameters along with empirical equations so that the results can be applied over a wide range of conditions and elbow sizes. A comparison of the 60° elbow with previous calculations for a comparable 90° elbow indicated that the impingement characteristics of the two elbows are very similar.

58 NACA TN 4092
National Advisory Committee for Aeronautics.
EXPERIMENTAL DROPLET IMPINGEMENT ON FOUR BODIES OF REVOLUTION. James P. Lewis and Robert S. Ruggeri. December 1957. 61p. diagrs., photos. (NACA TN 4092)

The rate and area of cloud droplet impingement on four bodies of revolution were obtained experimentally in the NACA Lewis icing tunnel. Spheres, ellipsoidal forebodies of fineness ratios of 2.5 and 3.0, and a conical forebody of 30° included angle were studied at angles of attack of 0° to 6°, rotational speeds up to 1200 rpm, and an airspeed of 157 knots. The results are presented in the form of dimensionless impingement parameters in order to cover a wide range of flight and atmospheric conditions.

59 NACA TN 4035
National Advisory Committee for Aeronautics.
IMPINGEMENT OF CLOUD DROPLETS ON 36.5-PERCENT-THICK JOUKOWSKI AIRFOIL AT ZERO ANGLE OF ATTACK AND DISCUSSION OF USE AS CLOUD MEASURING INSTRUMENT IN DYE-TRACER TECHNIQUE. R. J. Brun and Dorothea E. Vogt. September 1957. 52p. diagrs., tabs.
(NACA TN 4035)

The trajectories of droplets in the air flowing past a 36.5-percent-thick Joukowski airfoil at zero angle of attack were determined. The amount of water in droplet form impinging on the airfoil, the area of droplet impingement, and the rate of droplet impingement per unit area on the airfoil surface were calculated from the trajectories and cover a large range of flight and atmospheric conditions. With the detailed impingement information available, the 36.5-percent-thick Joukowski can serve the dual purpose of use as the principal element in instruments for making measurements in clouds and of a basic shape for estimating impingement on a thick streamlined body.

60 NACA RM E56E11
National Advisory Committee for Aeronautics.
USE OF TRUNCATED FLAPPED AIRFOILS FOR IMPINGEMENT AND ICING TESTS OF FULL-SCALE LEADING-EDGE SECTIONS. Uwe H. von Glahn. July 1956. 29p. diagrs., photos., tabs.
(NACA RM E56E11)

Experimental studies were made with an NACA 65_1-212 airfoil section truncated at the 30- and 50-percent-chord stations and equipped with a trailing-edge flap. When the truncated airfoils were compared with the full-chord airfoils, the velocity distribution and the impingement characteristics were similar with the flap properly deflected, but were altered substantially without flap deflection. Use of flapped truncated airfoils permits impingement and icing studies in icing tunnels to be conducted with full-scale leading-edge sections over a greater range of conditions than previously possible.

61 NACA TECHNICAL NOTE 1178

A FLIGHT INVESTIGATION OF THE THERMAL PERFORMANCE OF AN AIR-HEATED PROPELLER

John F. Darsow and James Selna

SUMMARY

Observations were made during flight in natural-icing conditions and by the collection of thermal data on the propeller during flight in clear air and in clouds at temperatures above freezing. The propeller was equipped with standard hollow steel blades which were altered to permit heated air to enter the blade cavities at the propeller hub and to leave the cavities at the blade tips. The distribution of air flow inside the blades was not controlled.

The observations in natural-icing conditions together with the thermal test data indicate that little or no protection to the leading-edge region of the propeller blades would result during flight in severe natural-icing conditions. In natural-icing conditions only light-icing conditions were encountered; however, ice accretions formed on the leading edges of the blades in the region of blade stations 30 to 40. The clear air and cloud tests showed the propeller blades to be inefficient heat exchangers in that more heat energy was discharged in the air flow leaving the propeller than was dissipated through the propeller-blade surfaces. The measured blade-surface temperatures indicated that inadequate heating was provided to the leading-edge region of the propeller and show the need of providing means to increase the heat flow through the leading-edge region of the blades.

62 **Icing and De-Icing of a Propeller with Internal Electric Blade Heaters**

By James P. Lewis and Howard C. Stevens, Jr.

NACA TN No. 1691
August, 1948

Abstract

De-icing effectiveness of internal electric propeller-blade heater was determined at two icing and two operating conditions with heat applied continuously and cyclically, and the required heat-on and cycle times are shown.

Chordwise extent of icing was greater than that covered by blade heaters. Adequate de-icing in heated area with continuous heating was obtained with power available but maximum power input of 1250 watts per blade was insufficient for cyclic de-icing. Surface temperature-rise rates of 0.2° to 0.7° F per second were obtained and minimum cooling period for cylic de-icing was approximately $2\frac{1}{2}$ times the heating period.

63 De-Icing Effectiveness of External Electric Heaters for Propeller Blades.

By James P. Lewis

NACA TN No. 1520
February 1948

Abstract

Icing protection provided by external rubber-clad propeller blade heaters at several icing, heating, and propeller operating conditions has been determined. Effects of propeller speed, ambient-air temperature, liquid water concentration, heating power density, duration of heating, and total cycle time on power requirements and de-icing performance were investigated.

Power densities of $4\frac{1}{2}$ to 10 watts per square inch were required for cyclic de-icing with best chordwise distribution approaching uniformity. Heating times of approximately 24 seconds were required with ratio of heat-on to total cycle time of 1:4 giving best results. Mean rate of rise of heater temperature of approximately 1.1° F per second was obtained.

64 An Electric Thrust Meter Suitable for Flight Investigation of Propellers.

By Porter J. Perkins and Morton B. Millenson

NACA RM No. E9C17
May 1949

Abstract

A lightweight instrument that utilizes resistance-wire electric strain gages to measure propeller-shaft thrust has been developed. A wind-tunnel investigation on a propeller installed on a single-engine pursuit airplane showed that the instrument gave a reliable indication of propeller-shaft thrust to an accuracy of ±2 percent within its calibrated range. No attempt was made to determine the relation of indicated shaft thrust to net propeller thrust.

65 Investigation of Effectiveness of Air-Heating a Hollow Steel Propeller for Protection against Icing. I - Unpartitioned Propeller Blades.

By Donald R. Mulholland and Porter J. Perkins

NACA TN No. 1586
May 1948

Abstract

An icing investigation of an air-heated hollow steel propeller with blades radially partitioned at 25-percent chord was conducted in the NACA Cleveland icing research tunnel.

Results showed that at 850 rpm a heating rate of 7000 Btu per hour per blade provided adequate icing protection at 23° F but not as low as 15° F. Surface temperatures indicated satisfactory chordwise distribution. The blade heat-exchanger effectiveness was found to be 77 percent.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE NO. 1587

INVESTIGATION OF EFFECTIVENESS OF AIR-HEATING A HOLLOW STEEL PROPELLER FOR PROTECTION AGAINST ICING

II - 50-PERCENT PARTITIONED BLADES

By Porter J. Perkins and Donald R. Mulholland

SUMMARY

The icing protection afforded an internal air-heated propeller blade by radial partitioning at 50-percent chord to confine the heated air to the forward half of the blade was determined in the NACA Cleveland icing research tunnel. A modified production-model hollow steel propeller was used for the investigation. Temperatures of the blade surfaces for several heating rates were measured under various tunnel icing conditions. Photographic observations of ice formations on blade surfaces and blade heat-exchanger effectiveness were obtained.

With 50-percent partitioning of the blades, adequate icing protection at 1050 rpm was obtained with a heating rate of 26,000 Btu per hour per blade at the blade shank using an air temperature of 400° F with a flow rate of 280 pounds per hour per blade, which is one-third less heat than was found necessary for similar ice protection with unpartitioned blades. The chordwise distribution of the applied heat, as determined by surface temperature measurements, was considered unsatisfactory with much of the heat dissipated well back of the leading edge. Heat-exchanger effectiveness of approximately 56 percent also indicated poor utilization of available heat. This effectiveness was, however, 9 percent greater than that obtained from unpartitioned blades.

67 **Investigation of Effectiveness of Air-Heating a Hollow Steel Propeller for Protection against Icing. III - 25-Percent Partitioned Blades**

By Donald R. Mulholland and Porter J. Perkins

NACA TN No. 1588
May 1948

Abstract

An icing investigation of an air-heated hollow steel propeller with blades radially partitioned at 25-percent chord was conducted in the NACA Cleveland icing research tunnel.

Results showed that at 850 rpm a heating rate of 7000 Btu per hour per blade provided adequate icing protection at 23° F but not as low as 15° F. Surface temperatures indicated satisfactory chordwise distribution. The blade heat-exchanger effectiveness was found to be 77 percent.

68 NACA TECHNICAL NOTE 1494

A METHOD FOR ESTIMATING HEAT REQUIREMENTS FOR ICE PREVENTION ON GAS-HEATED HOLLOW PROPELLER BLADES

V. H. Gray and R. G. Campbell

SUMMARY

The propeller blade is analytically divided into a number of short radial segments, successively treated as separate heat exchangers. Expressions for the total external and internal heat transfer are combined to determine the surface temperatures of each segment. The thermodynamic steady-flow equation is given for the internal gas-flow process and expressions are obtained for the radial variations of gas temperature and pressure within the blade. For a given initial gas temperature in the blade shank cavity, the minimum gas flow is determined, which will provide surface temperatures of at least 32° F everywhere on the heated portion of the blade. An expression for the required heat-source input to the gas is included and a formula is given for calculating the required blade-tip nozzle area.

69 **NACA TN 2852**
National Advisory Committee for Aeronautics.
AN INVESTIGATION UTILIZING AN ELECTRICAL ANALOGUE OF CYCLIC DE-ICING OF A HOLLOW STEEL PROPELLER WITH AN EXTERNAL BLADE SHOE. Carr B. Neel, Jr. December 1952. 54p. diagrs., photos., 3 tabs. (NACA TN 2852)

A study of the heat requirements for cyclic de-icing of hollow steel propellers fitted with external blade shoes, utilizing an electrical analogue, showed how energy requirements could be decreased by changes in the method of operation of existing shoes and through proper blade-shoe design. Savings in total energy in the order of 60 percent would be possible in each case. Energy requirements were shown to increase with decreasing liquid-water content and air temperature.

70 **NACA TN 3025**
National Advisory Committee for Aeronautics.
AN INVESTIGATION UTILIZING AN ELECTRICAL ANALOGUE OF CYCLIC DE-ICING OF HOLLOW STEEL PROPELLERS WITH INTERNAL ELECTRIC HEATERS. Carr B. Neel, Jr. October 1953. 31p. diagrs., photo., 3 tabs. (NACA TN 3025)

An analytical study, utilizing an electrical analogue, of the heat requirements for cyclic de-icing of hollow steel propellers fitted with two types of internal electric heaters showed the impracticability of using an internal tubular heater, and illustrated the advantages of employing an internal shoe-type heater to distribute the heat more evenly to the blade surface. The importance of minimizing the thermal inertia of the system was demonstrated, and the magnitude of reductions in the total energy requirement made possible through reductions in heating period was indicated.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2212

THE EFFECT OF ICE FORMATIONS ON PROPELLER PERFORMANCE

By Carr B. Neel, Jr., and Loren G. Bright

SUMMARY

Measurements of propeller efficiency loss due to ice formation are supplemented by an analysis to establish the magnitude of efficiency losses to be anticipated during flight in icing conditions. The measurements were made during flight in natural icing conditions; whereas the analysis consisted of an investigation of changes in blade-section aerodynamic characteristics caused by ice formation and the resulting propeller efficiency changes. Agreement in the order of magnitude of efficiency losses to be expected is obtained between measured and analytical results. The results indicate that, in general, efficiency losses can be expected to be less than 10 percent; whereas maximum losses, which will be encountered only rarely, may be as high as 15 or 20 percent. Reported losses larger than 15 or 20 percent, based on reductions in airplane performance, probably are due to ice accretions on other parts of the airplane.

Blade-element theory is used in the analytical treatment, and calculations are made to show the degree to which the aerodynamic characteristics of a blade section must be altered to produce various propeller efficiency losses. The effects of ice accretions on airfoil-section characteristics at subcritical speeds and their influence on drag-divergence Mach number are examined, and the attendant maximum efficiency losses are computed. The effect of kinetic heating on the radial extent of ice formation is considered, and its influence on required length of blade heating shoes is discussed. It is demonstrated how the efficiency loss resulting from an icing encounter is influenced by the decisions of the pilot in adjusting the engine and propeller controls.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE NO. 1790

INVESTIGATION OF ICING CHARACTERISTICS OF TYPICAL LIGHT-AIRPLANE ENGINE INDUCTION SYSTEMS

By Willard D. Coles

SUMMARY

The icing characteristics of two typical light-airplane engine induction systems were investigated using the carburetors and manifolds of engines in the horsepower ranges from 65 to 85 and 165 to 185. The smaller system consisted of a float-type carburetor with an unheated manifold and the larger system consisted of a single-barrel pressure-type carburetor with an oil-jacketed manifold.

Carburetor-air temperature and humidity limits of visible and serious icing were determined for various engine power conditions. Several methods of achieving ice-free induction systems are discussed along with estimates of surface heating requirements of the various induction-system components.

A study was also made of the icing characteristics of a typical light-airplane air scoop with an exposed filter and a modified system that provided a normal ram inlet with the filter located in a position to induce inertia separation of the free water from the charge air.

The principle of operation of float-type carburetors is proved to make them inherently more susceptible to icing at the throttle plate than pressure-type carburetors. The results indicated that proper jacketing and heating of all parts exposed to the fuel spray can satisfactorily reduce or eliminate icing in the float-type carburetor and the manifold. Pressure-type carburetors can be protected from serious icing by proper location of the fuel-discharge nozzle combined with suitable application of heat to critical parts.

73 ICING-PROTECTION REQUIREMENTS FOR RECIPROCATING-ENGINE INDUCTION SYSTEMS

By WILLARD D. COLES, VERN G. ROLLIN, and DONALD R. MULHOLLAND

SUMMARY

Despite the development of relatively ice-free fuel-metering systems, the widespread use of alternate and heated-air intakes, and the use of alcohol for emergency de-icing, icing of aircraft-engine induction systems is a serious problem. Investigations have been made to study and to combat all phases of this icing problem. From these investigations, criterions for safe operation and for design of new induction systems have been established.

The results were obtained from laboratory investigations of carburetor-supercharger combinations, wind-tunnel investigations of air scoops, multicylinder-engine studies, and flight investigations. Characteristics of the three forms of ice, impact, throttling, and fuel evaporation, were studied. The effects of several factors on the icing characteristics were also studied and included (1) atmospheric conditions, (2) engine and air-scoop configurations, including light-airplane systems, (3) type of fuel used, and (4) operating variables, such as power condition, use of a manifold pressure regulator, mixture setting, carburetor heat, and water-alcohol injection. In addition, ice-detection methods were investigated and methods of preventing and removing induction-system ice were studied. Recommendations are given for design and operation with regard to induction-system icing.

74 NACA RM E53E07
National Advisory Committee for Aeronautics.
INVESTIGATION OF AERODYNAMIC AND ICING CHARACTERISTICS OF A FLUSH ALTERNATE-INLET INDUCTION-SYSTEM AIR SCOOP. James P. Lewis. July 1953. 42p. diagrs., photos. (NACA RM E53E07)

An investigation of the aerodynamic and icing characteristics of a full-scale induction-system air-scoop assembly incorporating a flush-type alternate inlet was conducted in the NACA Lewis icing research tunnel. The investigation was made over a range of mass-air-flow ratios, angles of attack, airspeeds, air temperatures, liquid-water content, and droplet sizes. The ram inlet gave good pressure recovery in both clear air and icing, but rapid blocking of the carburetor screen occurred in icing. The alternate inlet had poor pressure recovery in both clear air and icing, but no serious screen icing was obtained. The investigation included the use of preheat air alone and in combination with ram- and alternate-inlet air.

Turbine-Type Engine and Inlet Icing Studies

75 Natural Icing of an Axial-Flow Turbojet Engine in Flight for a Single Icing Condition.

By Loren W. Acker

NACA RM No. E8F01a
August 12, 1948

Abstract

A flight investigation in natural icing conditions was conducted to determine the effect of ice formations on performance of axial-flow turbojet engines. Results are presented for a flight in which liquid-water content varied from 0.077 to 0.490 gram per cubic meter.

During 60 minutes in icing, tail-pipe temperature increased from 865° to 965° F and the jet thrust decreased from 1950 to 1700 pounds. The engine was satisfactorily accelerated to take-off power near the end of the icing period.

76 Preliminary Results of Natural Icing of an Axial-Flow Turbojet Engine.

By Loren W. Acker

NACA RM No. E8C18
August 1948

Abstract

A flight investigation in natural icing conditions was conducted to determine effect of ice formations on performance of an axial-flow turbojet engine. Results are presented for a flight in which the icing rate varied from 5.1 to 2.1 inches per hour.

During 45 minutes in icing, tail-pipe temperature increased from 761° to 1065° F and jet thrust decreased from 1234 to 910 pounds. Ice penetrated to the second-stage stator blades.

 C-2

77 **Icing Characteristics and Anti-Icing Heat Requirements for Hollow and Internally Modified Gas-Heated Inlet Guide Vanes.**

By Vernon H. Gray and Dean T. Bowden

NACA RM E50I08

December 1950

Abstract

Gas temperatures and flow rates required for anti-icing a two-dimensional cascade of turbojet inlet guide vanes were determined for hollow and internally modified vanes. The pressure losses caused by icing on unheated guide vanes were also determined.

Less heat was required for anti-icing internally modified blades than for the hollow blades. Pressure losses across the cascade were greater at an inlet temperature of 22° F than at 0° F because of the characteristic shapes of ice deposits at the two temperatures.

78 **NACA TN 3837**
National Advisory Committee for Aeronautics. INVESTIGATION OF HEAT TRANSFER FROM A STATIONARY AND ROTATING ELLIPSOIDAL FORE-BODY OF FINENESS RATIO 3. James P. Lewis and Robert S. Ruggeri. November 1956. 46p. diagrs., photo., tabs. (NACA TN 3837)

Experimental convective heat transfer was obtained for a 20-inch-diameter forebody for airspeeds up to 240 knots, rotational speeds up to 1200 rpm, angles of attack of 0°, 3°, and 6°, and both uniform surface temperature and uniform input heat density. The results agree well with theoretical predictions. Effects of rotation were insignificant, and effects of angle of attack only minor. Transition from laminar to turbulent heat transfer varied over a Reynolds number range of 0.8×10^6 to 5×10^6. Limited transient heating data indicated that the change of surface temperature with time followed an exponential relation.

79 NACA TN 4093
National Advisory Committee for Aeronautics.
INVESTIGATION OF HEAT TRANSFER FROM A STATIONARY AND ROTATING CONICAL FOREBODY. Robert S. Ruggeri and James P. Lewis. October 1957. 30p. diagrs., photo., tab. (NACA TN 4093)

Experimental convective heat transfer was determined for a conical forebody (15° half-angle) for free-stream velocities up to 400 feet per second, rotational speeds up to 1200 rpm, angles of attack of 0° and 6°, and for heating conditions of uniform surface temperature and uniform heater input power density. For the turbulent region, the results were in closer agreement with values predicted for two-dimensional bodies than with those predicted for a cone. Effects of rotation were insignificant. For the stationary spinner at 6° angle of attack, the heat-transfer coefficients were 6 to 13 percent greater on the lower surface than on the upper surface. Early boundary-layer transition occurred for all conditions investigated.

80 Investigation of Power Requirements for Ice Prevention and Cyclical De-Icing of Inlet Guide Vanes with Internal Electric Heaters.

By Uwe von Glahn and Robert E. Blatz

NACA RM E50H29

December 1950

Abstract

An investigation was conducted to determine the electric power requirements for turbojet-engine inlet guide vanes with continuous heating and with cyclical de-icing for a range of icing conditions.

Minimum total power requirements for continuous heating and cyclical de-icing are presented in terms of average surface datum temperature. An analysis is included to extend the experimentally obtained continuous heating data to vane sizes and icing conditions other than those investigated. Cyclical de-icing provides a total power saving as high as 79 percent over continuous heating for a typical engine installation. Heat-on periods of 10 seconds or less with heat-off periods of 60 seconds are recommended for cyclical de-icing.

81 NACA Investigations of Icing-Protection Systems for Turbojet-Engine Installations.

By Uwe von Glahn, Edmund E. Callaghan, and Vernon H. Gray

NACA RM E51B12

May 1951

Abstract

A summary is presented of the investigations made in flight and in wind tunnels at the NACA Lewis laboratory to determine which components of turbojet engines are most critical in icing conditions and to evaluate several icing-protection methods.

Complete removal or retraction of compressor-inlet screens upon entering icing conditions is recommended. Surface heating appears to be the most acceptable icing-protection method, although hot-gas bleedback offers a simple method for obtaining icing protection on some installations.

82 NACA RM E57G09
National Advisory Committee for Aeronautics.
TOTAL-PRESSURE DISTORTION AND RECOVERY OF SUPERSONIC NOSE INLET WITH CONICAL CENTERBODY IN SUBSONIC ICING CONDITIONS.
Thomas F. Gelder. September 1957. 41p. diagrs., photos. (NACA RM E57G09) CONFIDENTIAL

Ice was formed on a full-scale unheated supersonic nose inlet over a range of conditions in the NACA Lewis icing tunnel to determine its effect on compressor-face total-pressure distortion and recovery. The addition of ice to the inlet components increased distortion levels and decreased recovery values compared with clear-air results, the losses increasing with time in icing. The combination of glaze ice, high corrected weight flow, and high angle of attack yielded the highest levels of distortion and lowest values of recovery.

83 **Investigation of Aerodynamic and Icing Characteristics of Water-Inertia-Separation Inlets for Turbojet Engines.**

By Uwe von Glahn and Robert E. Blatz

NACA RM E50E03
July 1950

Abstract

Aerodynamic and icing investigations of several internal water-inertia-separation inlets designed to prevent entrance of water into a turbojet engine in an icing condition are presented. Comparisons of total-pressure loss, mass flow, and icing characteristics are made.

Complete icing protection of inlet guide vanes was not achieved. Approximately 8 percent of the volume of water entering the inlets remained in the air. For non-icing operation, total-pressure losses were comparable to those of direct-ram inlets. Under icing conditions, considerable total-pressure losses were obtained with inertia-separation inlets.

Wing Icing Protection

84 **AN ANALYSIS OF THE DISSIPATION OF HEAT IN CONDITIONS OF ICING FROM A SECTION OF THE WING OF THE C-46 AIRPLANE**

J. K. Hardy

SUMMARY

A method is given for calculating the temperature that a surface, heated internally by air, will assume in specified conditions of icing. The method can be applied generally to predict the performance, under conditions of icing, of the thermal system for protecting aircraft. Calculations have been made for a section of the wing of the C-46 airplane, and the results agree closely with the temperatures measured. The limit of protection, when the temperature of the surface reaches 32° F, has been predicted for the leading edge. The temperature of the surface in conditions of icing with air at 0° F also has been calculated. The effect of kinetic heating and the effect of the concentration of free water and size of droplet in the cloud are demonstrated.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE NO. 1472

THE CALCULATION OF THE HEAT REQUIRED FOR WING THERMAL ICE PREVENTION IN SPECIFIED ICING CONDITIONS

By Carr B. Neel, Jr., Norman R. Bergrun,
David Jukoff, and Bernard A. Schlaff

SUMMARY

As a result of a fundamental investigation of the meteorological conditions conducive to the formation of ice on aircraft and a study of the process of airfoil thermal ice prevention, previously derived equations for calculating the rate of heat transfer from airfoils in icing conditions were verified. Knowledge of the manner in which water is deposited on and evaporated from the surface of a heated airfoil was expanded sufficiently to allow reasonably accurate calculations of airfoil heat requirements. The research consisted of flight tests in natural-icing conditions with two 8-foot-chord heated airfoils of different sections. Measurements of the meteorological variables conducive to ice formation were made simultaneously with the procurement of airfoil thermal data.

It was concluded that the extent of knowledge on the meteorology of icing, the impingement of water drops on airfoil surfaces, and the processes of heat transfer and evaporation from a wetted airfoil surface has been increased to a point where the design of heated wings on a fundamental, wet-air basis now can be undertaken with reasonable certainty.

86 **NACA RM E51J29**
National Advisory Committee for Aeronautics. PRELIMINARY RESULTS OF CYCLICAL DE-ICING OF A GAS-HEATED AIRFOIL. V. H. Gray, D. T. Bowden and U. von Glahn. January 1952. 38p. photos., diagrs., tab. (NACA RM E51J29)

An NACA 65·-212 airfoil of 8-foot chord was provided with a gas-heated leading edge for investigations of cyclical de-icing. De-icing was accomplished with intermittent heating of airfoil segments that supplied hot gas to chordwise passages in a double-skin construction. Ice removal was facilitated by a spanwise leading-edge parting strip which was continuously heated from the gas-supply duct. Preliminary results demonstrate that satisfactory cyclical ice removal occurs with ratios of total cycle time to heat-on period from 10 to 26.

87 **NACA RM E51J30**
National Advisory Committee for Aeronautics. PRELIMINARY INVESTIGATION OF CYCLIC DE-ICING OF AN AIRFOIL USING AN EXTERNAL ELECTRIC HEATER. James P. Lewis and Dean T. Bowden. February 1952. 43p. photos., diagrs. (NACA RM E51J30)

An investigation was conducted in the NACA Lewis icing research tunnel to determine the characteristics and requirements of cyclic de-icing of an airfoil by use of an external electric heater. The present investigation was limited to an airspeed of 175 miles per hour. Data are presented to show the effects of variations in heat-on and heat-off periods, ambient air temperature, liquid-water content, angle of attack and heating distribution on the requirements for cyclic de-icing. The external heat flow at various icing and heating conditions is also presented. A continuously heated parting strip at the airfoil leading edge was found necessary for quick, complete, and consistent ice removal. The cyclic power requirements were found to be primarily a function of the datum temperature and heat-on time, with the other operating and meteorological variables having a second-order effect. Short heat-on periods and high power densities resulted in the most efficient ice removal, the minimum energy input, and the minimum runback ice formations.

88 **NACA TN 2480**
National Advisory Committee for Aeronautics. COMPARISON OF HEAT TRANSFER FROM AIRFOIL IN NATURAL AND SIMULATED ICING CONDITIONS. Thomas F. Gelder and James P. Lewis. September 1951. 51p. diagrs., photos., 2 tabs. (NACA TN 2480)

An experimental investigation of the heat transfer from an 8-foot-chord airfoil model in clear air and in simulated icing conditions was conducted in the icing tunnel. These results are compared with those obtained in a flight investigation with the same model at similar operating conditions. The tunnel results indicate the effect of tunnel turbulence by the forward movement of transition from laminar to turbulent heat transfer. The flight results indicate that the convective heat transfer in icing is considerably different from that measured in clear air and only slightly different from that obtained in the tunnel during simulated icing.

89 NACA TN 2914
National Advisory Committee for Aeronautics. A METHOD FOR RAPID DETERMINATION OF THE ICING LIMIT OF A BODY IN TERMS OF THE STREAM CONDITIONS. Edmund E. Callaghan and John S. Serafini. March 1953. 33p. diagrs. (NACA TN 2914)

The effects of existing frictional heating were analyzed to determine the conditions under which ice formations on aircraft surfaces can be prevented. A method is presented for rapidly determining by means of charts the combination of Mach number, altitude, and stream temperature which will maintain an ice-free surface in an icing cloud. The method can be applied to both subsonic and supersonic flow. The charts presented are for Mach numbers up to 1.8 and pressure altitudes from sea level to 45,000 feet.

90 NACA TN 2861
National Advisory Committee for Aeronautics.
ANALYTICAL INVESTIGATION OF ICING LIMIT FOR DIAMOND-SHAPED AIRFOIL IN TRANSONIC AND SUPERSONIC FLOW. Edmund E. Callaghan and John S. Serafini. January 1953. 18p. diagrs. (NACA TN 2861)

Calculations have been made for the icing limit of a diamond airfoil at zero angle of attack in terms of the stream Mach number, stream temperature, and pressure altitude. The icing limit is defined as a wetted-surface temperature of 32° F and is related to the stream conditions by the method of Hardy. The results show that the point most likely to ice on the airfoil lies immediately behind the shoulder and is subject to possible icing at Mach numbers as high as 1.4.

91 NACA RM E53C26
National Advisory Committee for Aeronautics.
DE-ICING AND RUNBACK CHARACTERISTICS OF THREE CYCLIC, ELECTRIC, EXTERNAL DE-ICING BOOTS EMPLOYING CHORDWISE SHEDDING. Robert S. Ruggeri. May 1953. 32p. photos., diagrs. (NACA RM E53C26)

The performance characteristics of three cyclic, electric, rubber-clad de-icing boots were evaluated. Each boot was operated in icing at design specifications of 21 watts per square inch for cycled areas, 13 watts per square inch for continuously heated parting strips, a heat-on time of 10 seconds, and a cycle ratio of 10. For a free-stream velocity of approximately 395 feet per second, the range of free-stream total temperature at which the icing protection afforded by the various boots became marginal was from 12° to 15° F for values of liquid-water content employed. The runback characteristics of the boots were similar. The forward cycled segments, upper and lower surfaces, were the most critical areas for the three boots investigated.

92 NACA RM E53C27
National Advisory Committee for Aeronautics.
COMPARISON OF SEVERAL METHODS OF CYCLIC DE-ICING OF A GAS-HEATED AIRFOIL. Vernon H. Gray and Dean T. Bowden. June 1953. 66p. diagrs., photos., 2 tabs. (NACA RM E53C27)

Several methods of cyclic de-icing of a gas-heated airfoil were investigated to determine ice-removal characteristics and heating requirements. The cyclic de-icing system with a spanwise ice-free parting strip in the stagnation region and a constant-temperature gas-supply duct gave the quickest and most reliable ice removal. Heating requirements for the several methods of cyclic de-icing are compared, and the savings over continuous ice prevention are shown. Data are presented to show the relation of surface temperature, rate of surface heating, and heating time to the removal of ice.

93 NACA TN 3130
National Advisory Committee for Aeronautics.
A PROCEDURE FOR THE DESIGN OF AIR-HEATED ICE-PREVENTION SYSTEMS. Carr B. Neel, Jr. June 1954. 63p. diagrs., photo. (NACA TN 3130)

The procedure to be followed in the design of aircraft ice-prevention equipment in which the components are protected by means of internally circulated heated air is outlined. In addition to presentation of the required heat-transfer and air-pressure-loss equations, a simple electrical analogue is described which was devised to facilitate the design of an air-heated system. An illustration is given of the application of the analogue to a design problem.

94 NACA RM E54I03
National Advisory Committee for Aeronautics.
INVESTIGATION OF POROUS GAS-HEATED LEADING-EDGE SECTION FOR ICING PROTECTION OF A DELTA WING. Dean T. Bowden. January 1955. 54p. diagrs., photos., tab. (NACA RM E54I03)

An investigation was conducted in the NACA Lewis icing research tunnel to determine heating requirements and characteristics of a gas-heated porous leading-edge system for anti-icing of a delta wing. Adequate icing protection was obtained for all icing conditions investigated. Large savings in gas flow may be realized by sealing half the upper-surface porous area. Gas flow through the porous area caused only a slight increase in airfoil drag and had no appreciable effect on airfoil pressure distribution. Glaze-ice formations on the unheated airfoil caused rapid increases in section drag.

95 NACA RM E56B23
National Advisory Committee for Aeronautics.
HEAT REQUIREMENTS FOR ICE PROTECTION OF A CYCLICALLY GAS-HEATED, 36° SWEPT AIRFOIL WITH PARTIAL-SPAN LEADING-EDGE SLAT. Vernon H. Gray and Uwe H. Von Glahn. May 1956. 73p. diagrs., photos., tabs. (NACA RM E56B23)

Heating requirements for satisfactory cyclic de-icing over a wide range of icing and operating conditions have been obtained for a gas-heated, 36° swept airfoil with a partial-span leading-edge slat. Comparisons of heating requirements were made between the slatted and unslatted portions of the airfoil and between cyclic de-icing and continuous anti-icing. Cyclic de-icing systems with and without leading-edge ice-free parting strips were also evaluated.

96 **Effectiveness of Thermal-Pneumatic Airfoil-Ice-Protectio~ System.**

By William H. Gowan, Jr., and Donald R. Mulholland

NACA RM E50K10a

April 1951

Abstract

Icing and drag investigations were conducted in the NACA L wis icing research tunnel on a thermal-pneumatic de-icer mounted on a 42-inch-chord NACA 0018 airfoil. Marginal power densities for the leading-edge electrically heated area were obtained. Drag comparisons were made between the bare airfoil and the various operating conditions of the pneumatic section of the de-icer during icing and nonicing of the airfoil surface.

Performance Penalties

97 **NACA RM E53J30**
National Advisory Committee for Aeronautics.
EFFECT OF ICE FORMATIONS ON SECTION DRAG OF SWEPT NACA 63A-009 AIRFOIL WITH PARTIAL-SPAN LEADING-EDGE SLAT FOR VARIOUS MODES OF THERMAL ICE PROTECTION. Uwe H. von Glahn and Vernon H. Gray. March 1954. 59p. diagrs., photos. (NACA RM E53J30)

Studies were made to determine the effect of ice formations on the section drag of a 6.9-foot-chord 36° swept NACA 63A-009 airfoil with partial-span leading-edge slat. In general, the icing of a thin swept airfoil will result in greater aerodynamic penalties than for a thick unswept airfoil. Glaze-ice formations at the leading edge of the airfoil caused large increases in section drag even at a liquid-water content of 0.39 gram per cubic meter. The use of an ice-free parting strip in the stagnation region caused a negligible change in drag compared with a completely unheated airfoil. Cyclic de-icing when properly applied caused the drag to decrease almost to the bare-airfoil drag value.

98 NACA TN 2962
National Advisory Committee for Aeronautics
EFFECT OF ICE AND FROST FORMATIONS ON DRAG OF NACA 65_1-212 AIRFOIL FOR VARIOUS MODES OF THERMAL ICE PROTECTION. Vernon H. Gray and Uwe H. von Glahn. June 1953. 68p. diagrs., photos. (NACA TN 2962)

Studies were made to determine the effect of ice and frost formations on the drag of an 8-foot-chord NACA 65_1-212 airfoil. At high angles of attack (8°), glaze-ice formations on the upper surface near the leading edge of an airfoil caused large increases in drag and incipient stalling of the airfoil. Runback icing on the lower surface, except for heavy spanwise ice ridges, presented no serious drag problems. Rime-ice formations on the leading edge did not cause large drag increases. Cyclic de-icing of the leading edge successfully decreased the drag almost to the bare airfoil drag value. Frost formations on airfoil surfaces caused large drag increases and may result in stalling of the airfoil.

99 Effects of Ice Formations on Airplane Performance in Level Cruising Flight.

By G. Merritt Preston and Calvin C. Blackman

NACA TN No. 1598
May 1948

Abstract

Flight investigation in natural icing conditions was conducted to determine effect of ice accretion on airplane performance.

Maximum loss in propeller efficiency encountered was 19 percent. During 87 percent of the propeller icing encounters, losses of 10 percent or less were observed. Ice formations on all components of the airplane except the propellers during one icing encounter resulted in an increase in parasite drag of the airplane of 81 percent. The control response of the airplane in this condition was marginal.

100 **NACA TN 2866**
National Advisory Committee for Aeronautics.
ICING PROTECTION FOR A TURBOJET TRANSPORT AIRPLANE: HEATING REQUIREMENTS, METHODS OF PROTECTION, AND PERFORMANCE PENALTIES. Thomas F. Gelder, James P. Lewis and Stanley L. Koutz. January 1953. i, 57p. diagrs., tab. (NACA TN 2866)

The heating requirements for several methods of icing protection for a typical turbojet transport airplane operating over a probable range of icing conditions are evaluated, and the airplane performance penalties associated with providing this protection from various energy sources are assessed. Continuous heating requirements and airplane penalties for the turbojet transport are considerably increased over those for lower-speed aircraft. Heating requirements can be substantially reduced by use of a cyclic de-icing system and choice of the proper energy source.

101 NACA TN 3564
National Advisory Committee for Aeronautics.
EFFECT OF PNEUMATIC DE-ICERS AND ICE FORMATIONS ON AERODYNAMIC CHARACTERISTICS OF AN AIRFOIL. Dean T. Bowden. February 1956. 59p. diagrs., photos. (NACA TN 3564)

Measurements of drag, lift, and pitching moment of an NACA 0011 airfoil were made in icing conditions using pneumatic de-icers having either spanwise or chordwise inflatable tubes. Lift and drag penalties due to de-icer inflation and to ice remaining after de-icer inflation are presented. Inflation of the spanwise-tube de-icer caused a much greater increase in drag than inflation of the chordwise-tube de-icer. The two de-icers were equally effective in removing ice. Lift and drag penalties resulting from ice formed with the de-icer inoperative are also presented, as well as spoiler data for analyzing drag increases due to ice formations.

102 NACA TN 4151
National Advisory Committee for Aeronautics.
CORRELATIONS AMONG ICE MEASUREMENTS, IMPINGEMENT RATES, ICING CONDITIONS, AND DRAG COEFFICIENTS FOR UNSWEPT NACA 65A004 AIRFOIL. Vernon H. Gray. February 1958. 45p. diagrs., photos., tabs. (NACA TN 4151)

An empirical relation is derived by which changes in section drag coefficients due to ice on an NACA 65A004 airfoil are calculable from known icing and operating conditions. The correlation is obtained by use of measured ice heights and ice angles. Initial ice weights are in agreement with droplet impingement data; in glaze conditions, ice weights increase at progressively greater rates with time.

103 NACA TN 4155
National Advisory Committee for Aeronautics.
AERODYNAMIC EFFECTS CAUSED BY ICING OF AN UNSWEPT NACA 65A004 AIRFOIL. Vernon H. Gray and Uwe H. von Glahn. February 1958. 47p. diagrs., photos., tabs. (NACA TN 4155)

At angles of attack less than 4° both rime and glaze-ice formations increased drag, reduced lift, and reduced diving moments. At angles of attack greater than 4°, drag coefficients increased with glaze-ice formations and decreased with rime ice; lift coefficients generally increased with glaze ice and were variably affected by rime ice; pitching-moment changes were rather erratic and depended on the ice shape. When the airfoil was iced at high angles of attack and rotated to lower angles, large negative pitching moments were obtained. Ice formations on the airfoil had no significant effects on control-surface hinge moments.

104 NASA TN D-2166
National Aeronautics and Space Administration.
PREDICTION OF AERODYNAMIC PENALTIES CAUSED BY ICE FORMATIONS ON VARIOUS AIRFOILS. Vernon H. Gray. February 1964. 19p. OTS price, $0.50.
(NASA TECHNICAL NOTE D-2166)

An equation is presented by which changes in drag coefficients due to ice formations on airfoils with thickness ratios up to 15 percent may be calculated from known icing and flight conditions. Based on limited data, changes in lift and pitching-moment coefficients due to ice on thick, blunt airfoils may be estimated from the corresponding changes in drag coefficients; for thin airfoils at higher angles of attack no general relation is obtained.

Windshield Icing Protection

105 NACA TECHNICAL NOTE 1434

A METHOD FOR CALCULATING THE HEAT REQUIRED FOR WINDSHIELD THERMAL ICE PREVENTION BASED ON EXTENSIVE FLIGHT TESTS IN NATURAL ICING CONDITIONS

Alun R. Jones, George H. Holdaway, and Charles P. Steinmetz

SUMMARY

An equation is presented for calculating the heat flow required from the surface of an internally heated windshield in order to prevent the formation of ice accretions during flight in specified icing conditions. To ascertain the validity of the equation, comparison is made between calculated values of the heat required and measured values obtained for test windshield in actual flights in icing conditions.

The test windshields were internally heated and provided data applicable to two common types of windshield configurations; namely the V-type and the type installed flush with the fuselage contours. These windshields were installed on a twin-engine cargo airplane and the icing flights were conducted over a large area of the United States during the winters of 1945-46 and 1946-47. In addition to the internally heated windshield investigation, some test data were obtained for a windshield ice-prevention system in which heated air was discharged into the windshield boundary layer.

106 **NACA RM E55E17a**
National Advisory Committee for Aeronautics.
PRELIMINARY DATA ON RAIN DEFLECTION FROM AIRCRAFT WINDSHIELDS BY MEANS OF HIGH-VELOCITY JET-AIR BLAST. Robert S. Ruggeri. July 1955. 17p. diagrs., photos. (NACA RM E55E17a)

Results indicate that rain deflection by jet-air blast appears feasible for flight speeds comparable with landing and take-off; however, visibility through the mist generated by raindrop breakup presents a problem. For the simulated windshield used, air-flow rates of about 3.3 lb/min-in. of span were required for adequate rain deflection at an airspeed of 135 mph. A method was devised whereby large-diameter water drops (1000 to 1500 μ) can be produced in a moving air stream, without breakup, at speeds in excess of 175 mph.

Cooling Fan Icing Protection

107 NACA TECHNICAL NOTE 1246

WIND-TUNNEL INVESTIGATION OF ICING OF AN ENGINE COOLING-FAN INSTALLATION

James P. Lewis

SUMMARY

An investigation was made of the icing characteristics and means of ice protection of a typical radial-engine cooling-fan installation. The investigation was made at various icing and performance conditions in the icing research tunnel of the NACA Cleveland laboratory.

The icing of the unprotected cooling-fan installation was found to present a serious operational problem. Reduction in air flow below the minimum value required for engine cooling-air flow through the fan assembly occurred in as little as 5 minutes under normal icing conditions.

Steam de-icing was found to be effective for the cowling lip and inlet duct. Alcohol de-icing of the fan blades and stator vanes was found to be unsatisfactory. Electrical heat de-icing of the fan blades was found to be effective but de-icing of the stator vanes was not completely effective at the power densities investigated.

108 NACA RM E53A22
National Advisory Committee for Aeronautics.
AN ANALYTICAL STUDY OF HEAT REQUIREMENTS FOR ICING PROTECTION OF RANDOMES.
James P. Lewis. March 1953. 20p. diagrs.
(NACA RM E53A22)

The heat requirements for the icing protection of two radome configurations have been studied over a range of design icing conditions. Both the protection limits of a typical thermal protection system and the relative effects of the various icing variables have been determined. For full evaporation of all impinging water, an effective heat density of 14 watts per square inch was required. When a combination of the full evaporation and running wet surface systems was employed, a heat requirement of 5 watts per square inch provided protection at severe icing and operating conditions.

109 NACA RM E52J31
National Advisory Committee for Aeronautics.
EXPERIMENTAL INVESTIGATION OF RADOME ICING AND ICING PROTECTION. James P. Lewis and Robert J. Blade. January 1953. 60p. diagrs., photos. (NACA RM E52J31)

In an investigation of radome icing and icing protection in the NACA Lewis icing research tunnel, the impingement of water and the formation of ice on two radome configurations were found to agree well with theory and experience. The ice formations on the radomes produced serious effects on radar performance. The ethylene glycol fluid-protection system gave adequate icing protection for both anti-icing and de-icing. The radomes were investigated at airspeeds up to 290 miles per hour, air total temperatures of -15° to 20° F, water contents up to 1.0 gram per cubic meter, and angles of attack of 0° and 4°.

Antenna Icing

110 Determination of Aircraft Antenna Loads Produced by Natural Icing Conditions.

By William L. Kepple

NACA RM No. E7H26a

February 1948

Abstract

Presents the effect of distance flown in the icing region, antenna length, and antenna angle on the tension occurring in aircraft antennas.

Antenna tension increased with antenna angle. The maximum tensions recorded were:

0° to 15°	- 68 pounds
44°	- 274 pounds
64°	- 438 pounds

111 Vibration and Icing Investigation of CAA Type V-109 Very-High-Frequency Aircraft Antenna.

By William H. Gowan, Jr.

NACA RM No. SE9D20

Abstract

Vibration and icing characteristics were investigated in the NACA icing research tunnel on a CAA type V-109 very-high-frequency aircraft antenna proposed for omnidirectional-range operation. Vibration of the antenna elements was observed for both icing and non-icing conditions. Maximum vibration amplitude observed was approximately 7 inches at the end of an element 24 inches long during icing, and failure of an element occurred in one instance during icing. Vibration without ice accretion was not severe.

Inlet and Vent Icing Protection

112 Investigation of Aerodynamic and Icing Characteristics of Recessed Fuel-Vent Configurations.

By Robert S. Ruggeri, Uwe von Glahn, and Vern G. Rollin

NACA TN No. 1789
March 1949

Abstract

An investigation was conducted to determine aerodynamic and icing characteristics of several recessed fuel-vent configurations.

The vent configuration having diverging ramp sidewalls, 7° ramp angle, and vent tubes manifolded to a plenum chamber gave greatest vent-tube pressures for all conditions investigated. Configurations with diverging ramp sidewalls gave greater vent-tube pressures than configurations with parallel sidewalls. In similar cloud-icing conditions, only the configuration with a plenum chamber maintained adequate vent-tube pressures throughout 60-minute icing periods. No complete closure of vent-tube openings due to ice formations occurred for configurations investigated.

Jet Penetration

113 NACA TECHNICAL NOTE 1615

INVESTIGATION OF THE PENETRATION OF AN AIR JET DIRECTED PERPENDICULARLY TO AN AIR STREAM

Edmund E. Callaghan and Robert S. Ruggeri

SUMMARY

An experimental investigation was conducted to determine the penetration of a circular air jet directed perpendicularly to an air stream as a function of jet density, jet velocity, air-stream density, air-stream velocity, jet diameter, and distance downstream from the jet. The penetration was determined for nearly constant values of air-stream density at two tunnel velocities, four jet diameters, four positions downstream of the jet, and for a large range of jet velocities and densities. An equation for the penetration was obtained in terms of the jet diameter, the distance downstream from the jet, and the ratios of jet and air-stream velocities and densities.

114 **Penetration of Air Jets Issuing from Circular, Square, and Elliptical Orifices Directed Perpendicularly to an Air Stream.**

By Robert S. Ruggeri, Edmund E. Callaghan, and Dean T. Bowden

NACA TN 2019
February 1950

Abstract

The penetration of air jets directed perpendicularly to an air stream was experimentally determined. Jets issuing from circular, square, and elliptical orifices were investigated and the penetration at a position downstream of the orifice was determined as a function of jet density, jet velocity, air-stream density, air-stream velocity, effective jet diameter, and orifice flow coefficient. Results are correlated in terms of dimensionless parameters and the penetrations obtained with various shapes are compared.

Greater penetrations were obtained with square orifices than with circular orifices of equal area.

115 Investigation of Flow Coefficient of Circular, Square, and Elliptical Orifices at High Pressure Ratios.

By Edmund E. Callaghan and Dean T. Bowden

NACA TN 1947

Abstract

An experimental investigation was conducted to determine orifice coefficients of a jet directed perpendicularly to an air stream as a function of pressure ratio and jet Reynolds number for elliptical, square, and circular orifices. Effect of air-stream velocity on jet flow was determined for three tunnel-air velocities. Equations for flow coefficient in terms of jet Reynolds number and pressure ratio were obtained for various shapes.

Excellent correlation was obtained between results for jet discharging into still air and results for jet discharging into moving air stream, provided that correct outlet pressure was used.

116 NACA TN 2855

National Advisory Committee for Aeronautics.
GENERAL CORRELATION OF TEMPERATURE PROFILES DOWNSTREAM OF A HEATED AIR JET DIRECTED AT VARIOUS ANGLES TO AIR STREAM. Robert S. Ruggeri. December 1952. 59p. diagrs., tab. (NACA TN 2855)

An experimental investigation was conducted to determine the temperature profile downstream of a heated-air jet directed at various angles to an air stream. The profiles were determined at two positions downstream of the jet as a function of jet diameter, jet density, free-stream density, jet velocity, free-stream velocity, jet total temperature, orifice flow coefficient, and jet discharge angles. A method is presented which yields a good approximation of the temperature profile in terms of dimensionless parameters of the flow and geometric conditions.

117 NACA TN 2466

National Advisory Committee for Aeronautics.
A GENERAL CORRELATION OF TEMPERATURE PROFILES DOWNSTREAM OF A HEATED AIR JET DIRECTED PERPENDICULARLY TO AN AIR STREAM. Edmund E. Callaghan and Robert S. Ruggeri. September 1951. 37p. diagrs. (NACA TN 2466)

An experimental investigation was conducted to determine the temperature profile downstream of a heated air jet directed perpendicularly to an air stream. The profiles were determined at several positions downstream of the jet as a function of jet density, free-stream density, jet velocity, jet temperature, free-stream velocity, and orifice flow coefficient. A method is presented which yields a good approximation of the temperature profile in terms of dimensionless parameters of the flow and geometric conditions.

118 Improvements in Heat Transfer for Anti-Icing of Gas-Heated Airfoils with Internal Fins and Partitions.

By Vernon H. Gray

NACA TN 2126
July 1950

Abstract

The effectiveness of internal finning in airfoils was analyzed to determine design variables by which local surface heat transfer may be efficiently controlled. Comparative investigations of gas-heated hollow airfoils indicate that surface-heating rates for ice prevention may be increased up to 3.5 times by the addition of metal fins and flow-confining partitions to the airfoil internal passage.

119 NACA TN 2799
National Advisory Committee for Aeronautics.
SIMPLE GRAPHICAL SOLUTION OF HEAT TRANSFER AND EVAPORATION FROM SURFACE HEATED TO PREVENT ICING. Vernon H. Gray. October 1952. 19p. diagrs. (NACA TN 2799)

Equations expressing the heat transfer and evaporation from wetted surfaces during ice prevention have been simplified and regrouped to permit solutions by simple graphical means. Working charts for quick and accurate anti-icing calculations are also included.

120 **NACA TN 3045**
National Advisory Committee for Aeronautics. ANALOGY BETWEEN MASS AND HEAT TRANSFER WITH TURBULENT FLOW. Edmund E. Callaghan. October 1953. 19p. diagrs. (NACA TN 3045)

An analysis of combined heat and mass transfer from a flat plate has been made in terms of Prandtl's simplified physical concept of the turbulent boundary layer. The results of the analysis show that for conditions of reasonably small heat and mass transfer, the ratio of the mass- and heat-transfer coefficients is dependent on the Reynolds number of the boundary layer, the Prandtl number of the medium of diffusion, and the Schmidt number of the diffusing fluid in the medium of diffusion. For the particular case of water evaporating into air, the ratio of mass-transfer coefficient to heat-transfer coefficient is found to be slightly greater than unity.

121 NACA TN 3104
National Advisory Committee for Aeronautics. EXPERIMENTAL INVESTIGATION OF SUBLIMATION OF ICE AT SUBSONIC AND SUPERSONIC SPEEDS AND ITS RELATION TO HEAT TRANSFER. Willard D. Coles and Robert S. Ruggeri. March 1954. 29p. diagrs., photo. (NACA TN 3104)

An experimental investigation was conducted in the 3.84- by 10-inch tunnel to determine the mass transfer by sublimation, heat transfer, and skin friction for an iced surface at subsonic and supersonic speeds. The results show that the Stanton numbers of sublimation and heat transfer were increased 40 to 50 percent for an iced surface of moderate roughness as compared with those obtained for a bare plate. For ice surfaces of equivalent roughness, the ratio of sublimation to heat-transfer Stanton numbers was found to be 0.90. Sublimation Stanton numbers obtained at a Mach number of 1.3 showed no appreciable deviation from those obtained at subsonic speeds. Sublimation as a means of removing ice formations of appreciable thickness is so slow as to be of little value in the de-icing of aircraft at high altitudes.

122 NACA TN 3143

National Advisory Committee for Aeronautics. EXPERIMENTAL DETERMINATION OF THERMAL CONDUCTIVITY OF LOW-DENSITY ICE. Willard D. Coles. March 1954. 12p. diagrs., photo. (NACA TN 3143)

The thermal conductivity of low-density ice has been computed from data obtained in an experimental investigation of the heat transfer and mass transfer by sublimation for an iced surface on a flat plate in a high-velocity tangential airstream. The results are compared with data from several sources on the thermal conductivity of packed snow and solid glaze ice. The results show good agreement with the packed-snow values, and the extension of the curves for packed snow to the solid ice regime indicates that the curves are applicable to ice over the entire density range.

123 NACA TN 3396

National Advisory Committee for Aeronautics. ICING LIMIT AND WET-SURFACE TEMPERATURE VARIATION FOR TWO AIRFOIL SHAPES UNDER SIMULATED HIGH-SPEED FLIGHT CONDITIONS. Willard D. Coles. February 1955. 33p. diagrs., photos. (NACA TN 3396)

The variation of wet-surface temperature and the conditions that will result in ice-free surfaces for high-speed flight through clouds were investigated experimentally. The results are compared with calculated values obtained with an analytical method. The analytical results were generally conservative, giving wet-surface temperatures 2° to 4° F lower than the experiments and predicting the formation of ice at values of ambient-air temperature up to 12° F higher than the experiments. The location of analytically determined critical regions on the bodies for the initial formation of ice was experimentally substantiated.

124 **NACA RM E53F02**
National Advisory Committee for Aeronautics. PRELIMINARY RESULTS OF HEAT TRANSFER FROM A STATIONARY AND ROTATING ELLIPSOIDAL SPINNER. U. von Glahn. August 1953. 35p. diagrs., photo., 2 tabs. (NACA RM E53F02)

The convective heat-transfer coefficients were determined for an ellipsoidal spinner of 30-inch maximum diameter for both stationary and rotating operation. The range of conditions studied included airspeeds up to 275 miles per hour, rotational speeds up to 1200 rpm, and angles of attack of zero and 4°. The results indicate that a higher heat transfer occurred with rotation of the spinner. Transition from laminar to turbulent flow occurred over a large range of Reynolds numbers primarily because of surface roughness of the spinner.

Miscellaneous

125 NACA Preprint No. 225

CORRELATION OF AIRFOIL ICE FORMATIONS AND THEIR AERODYNAMIC EFFECTS WITH IMPINGEMENT AND FLIGHT CONDITIONS

Vernon H. Gray

ABSTRACT

An empirical equation is developed by which changes in drag coefficients due to ice formations on an NACA 65A004 airfoil may be calculated from known icing and flight conditions; this equation is then extended to include available data for other airfoils up to 15-percent thickness ratio. The correlation was obtained primarily by use of ice heights and ice angles measured on the 4-percent thick airfoil. The final equation, however, does not include the ice measurements, but relates changes in drag coefficients due to ice with the following variables: icing time, airspeed, air temperature, liquid-water content, cloud droplet-impingement efficiencies, airfoil chord, angles of attack, and leading-edge radius-of-curvature.

Changes in lift and pitching-moment coefficients due to ice on an NACA 0011 airfoil are also related to the corresponding changrs in drag coefficients; additional data on lift and pitching-moment changes due to ice are limited to the 65A004 airfoil, for which complex trends preclude a relationship within the scope of this paper.

126 THE ICING PROBLEM

CURRENT STATUS OF NACA TECHNIQUES AND RESEARCH

Uwe H. von Glahn

ABSTRACT

Icing of aircraft components such as airfoil surfaces and engine-inlet systems creates a serious operational problem. Aircraft are now capable of flying in icing clouds without difficulty, however, because research by the NACA and others has provided the engineering basis for icing protection systems. This paper summarizes some of the techniques used in NACA programs to solve aircraft icing problems and indicates the scope of the data available for the design of aircraft icing protection systems. The NACA Lewis icing facilities, specific test equipment and techniques used in conducting tests in icing wind tunnels, and several icing instruments are discussed in detail.

127 NASA TECHNICAL MEMORANDUM X-54700
(Also NASA TM-82265)

SOME CONSIDERATIONS OF THE NEED FOR ICING PROTECTION

OF HIGH-SPEED, HIGH-ALTITUDE AIRPLANES

Uwe von Glahn

SUMMARY

The icing problems of high-speed, high-altitude aircraft are confined to climb and let-down conditions. The performance losses in icing can be minimized by the use of an icing protection system at the expense of structural complexities and installed weight. The elimination of airframe protection systems for aircraft subject only to short icing encounters appears attractive, provided the performance penalty due to icing is not excessive. This paper considers the performance penalty caused by icing during climb in terms of reduction in rate of climb and in range for aircraft without airframe icing protection and is intended to show only orders of magnitude rather than absolute values.

128 **NACA TN 4220**
National Advisory Committee for Aeronautics.
A FLIGHT EVALUATION AND ANALYSIS OF THE EFFECT OF ICING CONDITIONS ON THE ZPG-2 AIRSHIP. William Lewis and Porter J. Perkins, Jr. April 1958. 66p. diagrs., photos., tab. (NACA TN 4220)

Test flights conducted by the U. S. Navy in a number of typical icing conditions are described. The airship operated successfully in all icing conditions encountered, but the desirability of limited protection for certain components was indicated. Icing in clouds was confined to wires and small components, but freezing rain and drizzle produced some icing on the envelope also. Theoretical calculations are presented which suggest that, while hazardous icing in freezing rain can occur under certain meteorological conditions, the probability of encountering these conditions is very small in coastal areas and approaches zero 200 to 300 miles offshore.

129 NASA TECHNICAL MEMORANDUM X-54700
(Also NASA TM-82266)

ICING CONDITIONS TO BE EXPECTED IN THE OPERATION OF HIGH-SPEED, HIGH-ALTITUDE AIRPLANES

William Lewis

SUMMARY

This paper considers the specific problems concerned with the probable frequency and severity of icing conditions to be expected in the operation of high-speed, high-altitude aircraft, as compared with the icing conditions encountered on older types of aircraft. There are two general aspects of this problem. The first phase of this discussion will be concerned with the frequency and probably severity of icing conditions at high altitudes. High-altitude airplanes, however, must still climb and descend through the lower layers of the atmosphere where icing conditions are more frequent; therefore, the second phase of this discussion will deal with the effect of aerodynamic heating, due to high airspeed, on the icing potentialities of clouds encountered at low altitudes.

130 **NACA Conference on Aircraft Ice Protection**

June 26-27, 1947

SUMMARY

NACA's latest research results were presented in 15 papers at the June 1947 Conference on Aircraft Ice Prevention. The papers are compiled herein.

131 SOCIETY OF AUTOMOTIVE ENGINEERS PREPRINT NO. 424

HEAT REQUIREMENTS FOR ICE PREVENTION ON GAS-HEATED PROPELLERS

V. H. Gray

SUMMARY

The investigation has established that feasible rates of heated gas flow can provide ample surface heating of propeller blades except at the leading edge, where complete ice prevention requires large rates of gas flow, resulting in considerable wastage of heat elsewhere in the blade and at the discharge nozzle. This waste heat can be reduced to a small fraction of its original value by carefully designing the blade internal passage so that use is made of flow-confining partitions and metal fins attached at the blade leading edge.